

A Review of the Biology of the Green and Golden Bell Frog *Litoria aurea*

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ABSTRACT

The Green and Golden Bell Frog *Litoria aurea* is an unusual endangered frog species. It has a high public profile as many populations occur in areas affected by human activities. As a result, there has been considerable recent scientific and popular interest in the species. Despite the interest and large volume of documented information there has been no general review of the biology of the species. *Litoria aurea* is not typical of other endangered species. It has many attributes of a “weedy” or “colonizing” species. Like other such species, it is characterised by occurrence in disturbed or newly created sites, high fecundity and high dispersal ability. However, unlike many “colonizing” species that are very common, *L. aurea* is considered to be endangered. Though the decline of *L. aurea* is continuing as a result of ongoing threats, it should be possible to promote some recovery of the species through such strategies as increased legislative protection, conservation agreements, habitat manipulation, and control of the impacts of the introduced Plague Minnow *Gambusia holbrooki*. As in many similar situations, further research will be essential to provide the necessary information-base for the threats to be arrested and the opportunities to be pursued. In this paper we review all available published information with regard to the biology of *L. aurea*, and include some previously unpublished field observations. We consider the implications of this review in terms of recovery and/or management of the species and the extent of further research on *L. aurea* that could benefit the recovery process.

Keywords: Frog, endangered, *Litoria aurea*, biology, review

Introduction

The Green and Golden Bell Frog *Litoria aurea* is an endangered frog species in New South Wales. It was once one of the most commonly encountered frogs in southeastern Australia, but has declined greatly in distribution and abundance and is presently considered to be under a significant risk of extinction (Pyke and White 1996; Tyler 1997). It has disappeared from over 90% of its former range and is now found in only about 40 sites in New South Wales (White and Pyke 1996). Most of its present populations occur on private land and it may therefore be affected by ongoing and proposed development (Pyke and White 1996). One of its most significant populations in New South Wales is at the

Homebush Bay site of the Sydney 2000 Olympics (Lunney and Ayers 1993; Greer 1994; Pyke 1995; Salzberg 2000; Wangmann 2000). This has raised public interest in this species.

There has been much recent scientific interest in the species. It has been a focus in undergraduate reports (e.g., Lewis 1996; Bannerman 1998; Consterdine 1999), Honours research projects (e.g., Markwell 1984; Morgan 1995; van de Mortel 1996; Lewis 1997; Penman 1998), and Masters and PhD research projects (e.g., Dankers 1977; Humphries 1979; Hamer 1998; A. Hamer, University of Newcastle, pers. comm. 2000). An edition of *Australian Zoologist* was devoted to it (Pyke and Osborne 1996). It has also been the subject of several management plans (e.g., Fanning and White

1994; Interagency Advisory Group 1994; White 1995b, 1996, 1997a,b, 1998; van de Mortel et al. 1997; Bower and Goldingay 1998; Gray 1999; Grenadier and Mahony 1999; Parsons 1999) and introduction programs (e.g., Fanning 1996; Fanning and White 1994; Hobcroft 1997a).

Litoria aurea has been found to occur on a number of privately owned sites for which development proposals have been put forward, consequently it has been the subject of various documents that are required by the legal processes associated with development proposals. These include reports of fauna surveys on or near sites of proposed development (e.g., Wellington and Wells 1994), Environmental Impact Statements, prepared in accordance with the New South Wales Environmental Planning and Assessment Act 1992, such as that for proposed developments on the Kurnell peninsula (Royston 1996; Woodward-Clyde 1996), Fauna Impact Statements, prepared under the former New South Wales Endangered Species (Interim Protection) Act 1991, for proposed development at a number of sites (Greenacre - White 1993; Rosebery - Cogger 1993; Ravensworth - Resource Planning Pty Ltd 1994; Homebush Bay - Greer 1994, Pyke 1995, Australian Museum Business Services 1996c; Wyong - Andrews Neil 1994), Species Impact Statements, prepared under the current New South Wales Threatened Species Conservation Act 1995, for proposed development at several sites (Kurnell peninsula - Gunninah Environmental Consultants 1996, McKenzie Land Planning Services 1996, Australian Museum Business Services 1996a,b; Arncliffe - Manidis Roberts Consultants 1994, 1996, Gunninah Environmental Consultants 1996, White 1998), reviews of several of these Impact Statements (e.g., Cogger 1994), Decision Reports by the New South Wales National Parks and Wildlife Service (e.g., NSW National Parks and Wildlife Service 1994 - re proposed development at Rosebery), and Internal Reports by Local Councils in relation to their decision-making roles (e.g., Sutherland Shire Council 1997). In association with the approved development of *L. aurea* habitat, there is usually a required monitoring program and sometimes a requirement that a report on the outcomes of the monitoring be prepared. Such reporting is available in relation to development at Port Kembla (Lewis and Goldingay 1997a; Kevin Mills and Associates 1997).

Litoria aurea has featured prominently in legal proceedings concerning proposed development. A Commission of Inquiry was held with regard to

proposed development at the Mt Owen coalmine (Cleland 1994) and Australand Properties Pty Ltd took Sutherland Shire Council to the Land and Environment Court of New South Wales in relation to proposed development on the Kurnell Peninsula (Mahony 1997; Jensen 1997). A number of "Friends of the Green and Golden Bell Frog" groups have been formed, each one focusing on a particular local population of *L. aurea* (e.g., Marrickville population: Anonymous 1996; Davistown/North Avoca: Katajczak 1998).

Despite the interest and the large number of publications and reports dealing with *L. aurea*, there has been no general review of the biology of the species. Our aims were therefore to: review all available information with regard to the biology of *L. aurea*; consider any implications for recovery of the species; and consider research that could benefit the recovery process and our understanding of the biology of the species.

This review was developed using the strategy recommended in Pyke (2000). In addition, we have tabulated some of our recorded field observations of *L. aurea* that have been made over about 40 person-years (i.e., 1969-2001 for A.W.; 1994-2001 for G.P.). We divide our review into sections based on the level at which observations regarding the species are focused (i.e., species, individual, population, biological community), how these were made, and issues such as conservation and management of the species. Within each of these sections there are also sub-sections that reflect what is known about this species.

Biological review: *Litoria aurea* (Lesson, 1829)

Species level

Identification

Litoria aurea is an attractively coloured and marked frog with adults having the following general features (see also Barker and Grigg 1977; Cogger 2000; Robinson 1993a; Barker et al. 1995; White 1995a). The back is smooth with areas of green and/or copper colour. The belly is white or off-white. The tympanum is partly or completely copper-coloured. The dorsal aspect of the limbs is usually copper-coloured while the underside is typically off-white. The concealed portions of the axilla and groin are brightly coloured, being blue or light green. There is a canthal stripe that extends from the back of the eye over the tympanum and along the flank of the frog. It is thin and tricoloured with white uppermost, then gold and finally black.

On the side of the abdomen below the canthal stripe the skin is partly granular. The toes have conspicuous webbing which reaches most of the way up the penultimate phalanx. The fingers are unwebbed. The discs on the fingers and toes are relatively small and usually only the finger discs are wider than the finger stem (Moore 1957; McCann 1961; Barker and Grigg 1977; Barker et al. 1995). On the basis of these traits, several similar identification keys for members of the *L. aurea* complex in southeastern Australia have been developed (Cogger 2000; Robinson 1993a; Thomson et al. 1996).

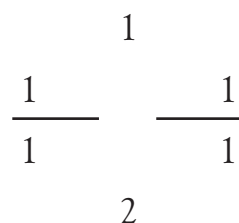
Individuals vary considerably over time in brightness of dorsal colouration. Dorsal colouration changes in response to temperature and microhabitat location. In the warmer months of the year, the backs of frogs that have been exposed to direct sunlight are generally brightly coloured with sharply contrasting green and copper patches (Pyke and White unpublished observations). During dry or cold periods, or when frogs are under shelter, the dorsal coloration darkens considerably and may become dull brown/black (Bell 1982b).

There is also considerable variation between individuals in dorsal colour pattern and recognition of individuals is sometimes possible on the basis of these differences (Clyne 1969a; Bell 1982a; Ford 1983, 1986; Greer 1994; Wellington 1995a; Murphy 1996; Grenadier and Mahony 1999; Bauer and Sadlier 2000). The dorsal stripes are not, for example, always present and the dorsum can be either completely green or completely copper-coloured (Pyke and White unpublished observations). In between these two extremes there is apparently a continuum of variation in terms of the sizes, shapes and locations of patches of green and copper (Pyke and White unpublished observations).

The eggs and egg masses of *L. aurea* are reasonably distinctive in appearance and can often be identified in the field. Amplexed females generally move and recross their paths during egg laying with the result that the egg mass is drawn out, often entangled around vegetation, and sometimes in more than one distinct unit (White unpublished observations). Initially the eggs are deposited at the water surface in a gelatinous medium in tangled floating sheets, usually around grass or other floating vegetation at the edges of still ponds (Fletcher 1889; Harrison 1922; Martin et al. 1966; Courtice 1972; Courtice and Grigg 1975; Barker and Grigg 1977; Bell 1982a,b; Ford 1983, 1986;

Hoser 1989; Hero et al. 1991; Barker et al. 1995; Morgan 1995; van de Mortel et al. 1998; Bauer and Sadlier 2000; White unpublished observations). The egg mass sinks within about one to four hours but remains attached to the vegetation (Harrison 1922; Martin et al. 1966; Courtice 1972; Courtice and Grigg 1975; Barker and Grigg 1977; Bell 1982a,b; Ford 1983, 1986; Hero et al. 1991; Barker et al. 1995; Morgan 1995; Bauer and Sadlier 2000; White unpublished observations). Eggs are small when initially laid, being about 2-2.5 mm across, and are bipolar, with one side black and the other white (Harrison 1922; Bell 1982a,b; Ford 1983, 1986; Bauer and Sadlier 2000). Upon being laid they immediately begin to swell, quickly reaching about 4 mm across, and then sink (White unpublished observations). When first laid they float with black side up, spread out in the gelatinous matrix, but after sinking egg orientation is more random (Bell 1982a; Ford 1983, 1986; White unpublished observations). There is no identification key to the eggs of *L. aurea* and other frog species, but sometimes it is the only possible species with an egg mass such as above and its eggs can then be recognised (White unpublished observations).

The shape of *L. aurea* tadpoles has been categorised by Anstis (1974) as "Type A" which she considers to be typical of tadpoles that are found in still ponds or very slowly flowing pools in a stream, often swim near the surface, but can remain hovering at any level in the water by rapidly undulating the fine tail tip. *L. aurea* has stout tadpoles with long, broad tails (Anstis 1974), relatively deep bodies and high fins, suggesting an actively swimming lifestyle (Barker and Grigg 1977; Tyler and Davies 1993; Barker et al. 1995). The deep tail fins enable sudden changes of direction, much like the action of a rudder on a boat (Anstis 1974). They have ventrally oriented mouths and a discrete tip to the tail. Tadpole mouthparts are easily seen in larger tadpoles and are arranged as follows:



(see White 1995a). The beaks, teeth and circumoral papillae of *L. aurea* tadpoles are illustrated in McCann (1961).

Identification of *L. aurea* on the basis of tadpoles is generally difficult as descriptions of the colouration of its tadpoles have varied considerably and there is no clear, consistent description of them. Fletcher (1989) stated that they are green in their later stages and acquire golden streaks before leaving the water. White (1995a) described them as having a dorsal base colour which is variable, being either dull brown or dirty yellow, with two dark bands of pigment extending from the snout, and broader, dark bands extending posteriorly from the eyes (see illustrations in White 1995a) and with body flanks which have a metallic lustre that is best seen in bright light. According to Hamer (1998) and Grenadier and Mahony (1999) the tail is dirty yellow in colour, the body flanks may have a metallic golden lustre, with two dark narrow lines of pigment running from tip of snout, between the eyes to the rear of body, and, in bright sunlight, a white canthal line may be seen on each side of the head. Hero et al. (1991) described *L. aurea* tadpoles as being pinkish-grey with yellowish fins. Hobcroft (1997b) reported that their conspicuous features are off-white ventral surfaces often with a golden sheen dorso-laterally. Bauer and Sadlier (2000) stated that they are yellowish-green to greenish-brown dorsally, with a lighter venter. Clearly, dorsal colour is not a reliable guide for the identification of Green and Golden Bell frog tadpoles.

Tadpoles of *L. aurea* can more easily be recognised on the basis of body markings. They sometimes exhibit an early development of the distinctive canthal stripe (Fletcher 1889; White unpublished observations), which initially consists of a row of silver chromatophores along each flank in tadpoles over 1 cm SVL (i.e., snout-vent length). This is not always easy to see and is best viewed under bright light (White unpublished observations). There is presently no published key that identifies tadpoles of *L. aurea* from other frog species. Sometimes, however, the tadpoles of *L. aurea* are sufficiently different in appearance from those of other co-occurring species to enable their identification (White unpublished observations).

Litoria aurea is a large species in terms of both tadpoles and adult frog sizes. Tadpoles of this species generally range in SVL from about 3 mm, when just hatched, to about 30 mm at metamorphosis, and in total body length from about 5 to 100 mm (Barker and Grigg 1977; Bell 1982a; Ford 1983, 1986; Barker et al. 1995;

Morgan 1995; Hobcroft 1997b; Penman 1998; Bauer and Sadlier 2000; White unpublished observations). Even longer individuals are sometimes observed in New Zealand (Bell 1982a) and, of the known hylid tadpoles, that of *L. aurea* is one of the largest (Anstis 1974). Adult frogs generally range from about 55 to 90 mm in SVL (Clyne 1969a; Moore 1961; Courtice 1972; Barker and Grigg 1977; Barker et al. 1995; White 1995a, Grenadier and Mahony 1999; Bauer and Sadlier 2000; Pyke and White unpublished observations) and some individuals as large as about 100 mm SVL have been reported (Hoser 1989; Hero et al. 1991; Pyke and White unpublished observations). Few other Australian frog species are as large (Cogger 2000).

Species distribution

The original natural distribution of *L. aurea* extended along the eastern coast of Australia from northern New South Wales to southern Victoria and included populations on the western slopes and tablelands of New South Wales (e.g., White and Pyke 1996; Cogger 2000).

The distribution of *L. aurea* has declined markedly, especially in New South Wales. Here *L. aurea* was formerly widespread in coastal swamps and lagoons south from about Byron Bay, and in wetlands on the western slopes and tablelands from about Bathurst to the southern highlands (Pyke and White 1996). Almost all populations on the slopes and tablelands appear to now be extinct, many coastal populations have also disappeared, and the species is presently restricted to about 40 sites, most of which are in the Greater Sydney Region (McArtney 1968, 1992; Osborne 1990, 1992; Mahony 1993, 1997; Daly 1995; Osborne et al. 1996; Pyke and White 1996; Bennett 1997; Lewis and Goldingay 1997b; Tyler 1997; White and Pyke 1999; Scanlon 2000). A population of *L. aurea* has been recently discovered near Queanbeyan on the southern tablelands (Wassens and Mullins 2001). *L. aurea* formerly occurred at sites with elevations between sea level and 1000 m, but now the higher elevation populations are almost all apparently extinct and the species is almost exclusively found below 150 m (Pyke and White 1996; White and Pyke unpublished observations). *L. aurea* has been reported from the tablelands area around Armidale (Heatwole et al. 1995; Webber 1995), but all available specimens from this area have recently been identified as *Litoria castanea* (M. Mahony, University of Newcastle, pers. comm. 1997).

Declines in Victoria have been less apparent. Here *L. aurea* is a primarily coastal species, occurring commonly in coastal swamps and lagoons east of about Orbost and in some inland wetlands adjacent to upstream portions of some of the river systems in this area (Gillespie 1996; Pyke and White unpublished observations.). Most coastal populations appear to have remained extant up to the present. However, for some of the more inland populations, there is apparently no remaining breeding habitat and the species has not been recently recorded (Gillespie 1996; Pyke and White unpublished observations.).

Litoria aurea has been introduced to several sites within its natural distribution, including three within the Sydney area (i.e., Sir Joseph Banks Park in the suburb of Botany: White 1995b; Fanning 1996; Hobcroft 1997a; White unpublished observations; Marrickville Community Centre in Marrickville: Cawood 1997; Long Reef Golf Course in Collaroy: Pyke unpublished observations) and one proposed near Bega on the south coast of New South Wales (Anonymous 2000).

Translocations of *L. aurea* outside of Australia have also expanded its distribution. It has been introduced into New Zealand, New Caledonia, Vanuatu, Loyalty Islands and the islands of Wallis and Futuna (Thomson 1922; Moore 1961; McCann 1961; Bell 1982a,b; Bull and Whitaker 1975; Gibbons 1985; Tyler 1976, 1979a,b, 1982; Ford 1983, 1986; Robb 1986; Pickard and Towns 1988; Osborne 1992; Glasby et al. 1993; Gill 1986; Greer 1994; Bauer et al. 1997; Bauer and Sadlier 2000). The species was initially introduced to New Zealand in the 1860s and it is now widely dispersed across the northern part of the North Island, north of about the latitude of Rotorua (McCann 1961; Tyler 1976, 1982; Bell 1982a,b; Gill 1986; Ford 1983, 1986; Robb 1986; Pickard and Towns 1988; Gill and Whitaker 1996; Pyke and White unpublished observations.). At most of these locations it is the only frog species present and at some of them it is locally abundant (Bell 1982a; Gill 1986; McCann 1961; Pyke and White unpublished observations.). The species was introduced into New Caledonia in the late nineteenth century and it is now widespread and locally abundant there (Sarasin 1925; Tyler 1976, 1979b, 1982; Greer 1994; Bauer and Sadlier 2000). The species was introduced into Vanuatu in about 1960 and it is apparently now abundant on some of these islands (Tyler 1976, 1979a,b, 1982).

There is some evidence that *L. aurea* may have recently declined in New Zealand (Barnett 2000). According to McCann (1961), one or other of the two introduced bell frogs were found in most streams and pools throughout New Zealand, but when detailed location details were assimilated more recently the total *L. aurea* records were very scattered and numbered only about 70 (Pickard and Towns 1988). It has also apparently disappeared from some of the recorded sites, where *Gambusia* is now present. The presence of this fish is the most likely cause of these losses (Pyke and White unpublished observations.).

The original distribution of *L. aurea* in New South Wales lies within the distribution boundaries predicted by climate, but other factors are also in operation. Based on the bioclimatic modelling approach of Busby (1991) and a number of known past and present locations for *L. aurea*, Ayers et al. (1996) have derived a predicted distribution for the species in New South Wales that extends along virtually the entire coastline and throughout much of the slopes and tablelands of the state (Ayers et al. 1996). The absence of the species from the more northerly parts of this predicted distribution could have resulted from interactions with other species such as *L. castanea*, which was relatively abundant in the northern tablelands. This approach could be further evaluated by applying it to New Zealand, New Caledonia, Vanuatu and Victoria.

Taxonomy and phylogeny

Litoria aurea is a member of a large Australian genus, with about 45 congeneric species in Australia (Cogger 2000). It was described by Lesson (1829). *Litoria* is one of three Australian genera in the family Hylidae (Cogger 2000).

Litoria aurea is presently considered part of a complex of seven phylogenetically closely related species with similar life histories (Steindachner 1867; Martin and Watson 1971; Courtice 1972; Courtice and Grigg 1975; King et al. 1979; King 1980; Maxson et al. 1982; King 1985; Watson and Littlejohn 1985; Hutchinson and Maxson 1987; King 1993; Watson 1993; Thomson et al. 1996; Mahony 1999). It is generally accepted that, in addition to *L. aurea*, this complex includes the following species (taking common names from Tyler 1992): Southern Bell Frog (*L. raniformis*), Yellow Spotted Tree Frog (*L. castanea*); Moore's Frog *L. moorei*, Dahl's Aquatic Frog *L. dahlui*, Striped Burrowing Frog *L. alboguttata*, Spotted Thighed Frog *L.*

cyclorhynchus (Barker and Grigg 1977; Tyler and Davies 1978; King 1980, 1993; Tyler 1982; Maxson et al. 1982; Watson and Littlejohn 1985; Watson 1993; Barker et al. 1995; Thomson et al. 1996; Mahony 1999), though *L. alboguttata* has not always been included in the group (White and Pyke 1999). We consider *L. castanea* and *L. flavipunctata* to be synonymous, with the former name having priority and therefore being adopted (Steindachner 1867; Courtice 1972; Courtice and Grigg 1975; Cogger et al. 1983; Thomson et al. 1996). Members of the species complex have been found to share a particular karyotype pattern (King 1985, 1993), as well as a number of osteological, myological and external characters (Tyler and Davies 1978). Courtice (1972) confirmed the distinctness of the three southeastern species *L. aurea*, *L. raniformis* and *L. castanea* by in vitro fertilisation experiments and electrophoretic studies.

Thompson et al. (1996) cite evidence that there was another species member of the complex that lived in the Southern Tablelands area, and propose the name *L. australopunctata* for it. This species, as well as *L. castanea*, are believed to now be extinct (Thomson et al. 1996; White and Ehmann 1997a,b; Pyke and White 1999).

Wells and Wellington (1985) have also recommended some further enlargement of this *L. aurea* species complex through the elevation of two populations to species status. They recommend that the population from near Ulong, New South Wales and labelled as *L. aurea ulongae* by Copland (1957) be considered a separate species. They also recommend that the Tasmanian population of *L. raniformis*, labelled as the subspecies *L. a. major* by Copland (1957), be considered a separate species. They also recommend changing the name of the genus *Litoria* to *Ranoidea*, and their proposed names for these two additional species are *Ranoidea ulongae* and *R. major*. These recommendations have not, however, been adopted.

Within this species complex, *L. aurea* is equally and most closely related to *L. raniformis* and *L. castanea*. A quantitative micro-complement fixation technique using serum albumins has suggested that the species most closely related to *L. aurea* is *L. raniformis*, but *L. castanea* was not considered in this study (Maxson et al. 1982). Albumin immunological distance data indicate that there is no differentiation between *L. raniformis* and *L. castanea*, and that *L. aurea*

separated from both *L. raniformis* and *L. castanea* about 1.1 million years ago (Roberts and Maxson 1988). In a study by Sherwin (1995) of protein variations in *Litoria aurea* and *L. raniformis*, 4 of 19 protein systems were found to show variation and just two of these showed differentiation between the two species.

Some of the early studies that refer to *L. aurea* were in fact studies of *L. raniformis*. Prior to 1972, *L. aurea* and *L. raniformis* were not differentiated as species and were both considered to be *L. aurea* (e.g., Krefft 1866; Fletcher 1892, 1894; Loveridge 1935; Parker 1938; Copland 1957; McCann 1961; Clyne 1969a,b; Courtice 1972; Courtice and Grigg 1975; Robb 1986). It is, however, generally possible to determine which of these two species is being considered on the basis of the geographic locations of captures or observations (Bell 1982a; see Section 1.2.8).

Hybridisation and sub-specific variation

There continues to be the potential for hybridisation to occur between *L. aurea* and other members of its species group. The distribution of *L. aurea* overlapped with that of *L. castanea* and *L. australopunctata*, and still does with *L. raniformis* in both Australia and New Zealand (Littlejohn et al. 1963; Courtice 1972; Brook 1975; Courtice and Grigg 1975; Bell 1982a,b; Ford 1983, 1986, 1989; Ayers et al. 1996; Pyke and White unpublished observations). *Litoria aurea* and *L. raniformis* presently overlap in distribution in East Gippsland and in the North Island of New Zealand, and formerly had a similar overlap area in the Australian Capital Territory (Littlejohn et al. 1963, 1993; Courtice 1972; Courtice and Grigg 1975; W. Sherwin, reported in Watson and Littlejohn 1985, Ford 1989; Ayers et al. 1996; Gillespie 1996 and Tyler 1997). Within these areas of overlapping distribution the two species are sometimes found together at the same pond (Littlejohn et al. 1963; Courtice 1972; Brook 1975; Courtice and Grigg 1975; Bell 1982a; Ford 1983, 1986; Pyke and White unpublished observations).

Despite co-occurrence of *L. aurea* and *L. raniformis* in some ponds, there is little evidence of hybridisation occurring between them (Littlejohn et al. 1963; Courtice 1972; Courtice and Grigg 1975; Humphries 1979; Bell 1982a; Watson and Littlejohn 1985; Ford 1989; Littlejohn et al. 1993). Sherwin found individuals with possibly intermediate features in East Gippsland suggesting some degree of inter-breeding and

hybridisation between the species (Watson and Littlejohn 1985; Ford 1989; Littlejohn et al. 1993; Gillespie 1996; Tyler 1997). Courtice, however, a study based on serum proteins, haemoglobin and eye lens proteins, found no evidence of such hybridisation in samples taken from both East Gippsland and the Australian Capital Territory (Courtice 1972; Courtice and Grigg 1975). No apparent hybridisation between these two species has been found at ponds in New Zealand where they co-occur (B. Bell, University of Wellington, pers. comm. 1997; White and Pyke unpublished observations). There were ponds in the Southern Tablelands and also possibly around Bathurst, New South Wales where *L. aurea* and *L. flavipunctata* occurred together (Humphries 1979; Thomson et al. 1996; White and Pyke 1999) with no suggestion of intergradation or intermediates between the two species (Thomson et al. 1996).

The number of recognised subspecies of *L. aurea* is presently two, but has varied between two and four. Loveridge (1950) recognised four subspecies - *L. a. aurea*, *L. a. raniformis*, *L. a. ulongae* and *L. a. cyclorhynchus*, while Copland (1957) recognised a slightly different set of four subspecies - *L. a. aurea*, *L. a. raniformis*, *L. a. ulongae* and *L. a. major*. However, *L. a. aurea*, *L. a. cyclorhynchus* and *L. a. raniformis* are now recognised as distinct species (Copland 1957; Courtice and Grigg 1975), and *L. a. major* is considered synonymous with *L. raniformis* (Copland 1957). At present *L. a. ulongae* and *L. a. aurea* are the only subspecies that are still recognised (Cogger et al. 1983).

There is little or no evidence of geographic variation in size or appearance within the major subspecies *L. a. aurea* and hence no present basis for further subspecific recognition. Any apparent regional variations in body markings cannot be differentiated from the high levels of variation within populations (White unpublished observations). There is also no apparent variation in size from one region to another. There is, in particular, no clear difference in average body size of *L. aurea* between New Zealand and Australia. For *L. aurea* in New Zealand, McCann (1961) reported that adult males are generally 60-65 mm SVL and adult females 80-90 mm, Bell (1982a,b) reported that most individuals are less than 75 mm SVL with some reaching about 80 or 90 mm, and Gill (1986) reported that the maximum size is about 80 mm SVL. In Australia, adult males are generally observed to be about 55 to 70

mm SVL in the wild and occasionally reaching about 70-80 mm, while adult females are usually 70 to 85 mm and occasionally 85-90 mm SVL (Clyne 1969a; Moore 1961; Courtice 1972; Barker and Grigg 1977; Barker et al. 1995; White 1995a, Grenadier and Mahony 1999; Pyke and White unpublished observations). Some individuals as large as about 100 mm SVL have been reported (Hoser 1989; Hero et al. 1991; Pyke and White unpublished observations).

Sex/age categories

We recognise the following five successive stages in the developmental process as *Litoria aurea* develops from egg through free-swimming tadpole to frog: egg, tadpole, metamorphling, immature frog, adult frog. Eggs are immotile and consist of a small, roundish embryo surrounded by a gelatinous yolk-filled capsule (Tyler and Davies 1978; Bell 1982). Free-swimming tadpoles hatch from these eggs. Initially they have no limbs but subsequently develop hind limbs, followed by front limbs. When both front and hind limbs have developed the animals are categorised as metamorphlings. Metamorphlings differ from later stages in retaining a tail that is resorbed during this stage. After metamorphosis is complete, immature frogs continue to grow and with time become reproductively mature adults. They continue to grow as adults. Growth and development through these stages is described in more detail below.

Litoria aurea can be sexed and aged on the basis of body size and the presence/absence of visible raised "nuptial" pads on their thumbs. Males that are about 50 mm SVL or longer have these pads and exhibit adult reproductive behaviour (see below); females do not develop them at all. During the breeding season the nuptial pads, which are believed to help them to grip females during amplexus, are very dark brown/black in colour. During the remainder of the year they fade and may become off-white or pinkish in colour, but are still recognisable. We use this characteristic for field sexing of frogs that are 50 mm in SVL or longer, and consider male frogs smaller than 50 mm SVL to be immature. Male frogs also often have a dirty yellow-brown or grey patch beneath the throat, whereas adult females usually have a white throat. It has been suggested that females may have fewer and/or smaller copper areas on the back and hence may be generally "greener" than males (Daly 1995), though, at least in some areas, this seems not to be the case (R. Goldingay, Southern Cross

University, pers. comm. 1999; Pyke and White unpublished observations). It has also been suggested that the feet of breeding male *L. aurea* are rusty orange, while the feet are bluish in females (McCann 1961; R. Goldingay, Southern Cross University, pers. comm. 1999). On the basis of observations of adult reproductive behaviour (see below), we consider female frogs less than 65 mm SVL to be immature, and larger females to be adults. It is not presently possible to sex immature individuals that are less than 50 mm SVL. Others have adopted a single size threshold separating adults from immatures, though the value of threshold has varied from 40 mm (e.g., Lewis and Goldingay 1997a) to 45 mm (Hamer 1998) to 50 mm (van de Mortel and Goldingay 1997; Goldingay and Lewis 1999).

There is apparently little error associated with sexing frogs of *L. aurea*. Some error seems inevitable, as there is likely to be variation in the SVL at which males develop nuptial pads and males that are perhaps slightly longer than 50mm but have not yet developed nuptial pads could be misidentified as females. Such errors would show up, in studies employing mark/recapture methods, as individuals that appear to change sex from female to male. Fortunately, we have found such occurrences to be rare (Pyke and White unpublished observations). However, in order to properly validate the present methodology, it will be necessary either to develop ways to reliably sex individuals that are smaller than 50mm SVL on the basis of externally visible characteristics or to follow growth and development in individual immature frogs until their sex is clear.

Habitat

Most descriptions of the habitat of *L. aurea* are very general and do not provide a good basis to predict either where the species is most likely to occur or where it is most likely to be able to reproduce successfully. Though clearly not a forest species (e.g., Lemckert 1996), *L. aurea* has otherwise been recorded in a wide variety of habitats. These include wetlands, marshes, swamps, ponds, dams, ditches, creeks, rivers, watering troughs, and various human containers such as baths and laundry tubs (e.g., Fletcher 1892; Courtice 1972; Courtice and Grigg 1975; Timms 1975; Bell 1982b; Cree 1984; Robb 1986; Wellington 1995a; Lunney and Barker 1986; Hero et al. 1991; Robinson 1993; Ehmann 1996; Tyler 1997; White and Pyke 1999; Bauer and Sadlier 2000).

We have produced a more detailed habitat description for *L. aurea* based on the habitat properties of sites in New South Wales, Victoria and New Zealand. We compared breeding and non-breeding sites for the species in New South Wales (Pyke and White 1996; Pyke et al. 2001). There were no apparent habitat differences between these three regions (Pyke et al. 2001) and the habitat most likely to support a breeding population of *L. aurea* had the following properties:

- Water bodies with a substrate of sand, rock or clay;
- Water bodies that are still, shallow, not too saline (i.e., less than about 7-8 parts per thousand) and reasonably unpolluted and should fluctuate significantly in water level. Such water bodies are most likely to occur in areas that experience disturbance (either natural or unnatural) and where surface water runoff from local unpolluted areas collects to form temporary ponds.
- Water bodies that are unshaded and free of *Gambusia* and other predatory fish;
- Emergent aquatic plants, such as *Typha* sp. or *Eleocharis* sp.;
- A range of possible diurnal shelter sites available, including thick low vegetation or rocks.
- A grassy area reasonably near to water bodies; other nearby vegetation consisting of woodland or shrubland with a maximum height of less than 2m (Specht 1970);

Litoria aurea tolerates a wide range of physical and chemical water properties. Tadpoles of this species have been found in water showing very wide ranges of turbidity, dissolved oxygen, oxidation reduction potential, pH and water temperature (Pyke et al. 2001). In addition, though its breeding ponds generally lack visible signs of pollution (Pyke and White 1996), many of these breeding ponds are, by virtue of their water catchments, likely to receive significantly polluted water (Pyke et al. 2001).

Throughout its entire range *L. aurea* is typically found in human-disturbed or human-created sites. At all the known sites where *L. aurea* occurs in New Zealand and almost all those in New South Wales, frog habitat is largely or completely human-made (Pyke and White 1996; Australian Museum Business Services 1996a,b; Pyke et al. 2001). Within these two areas the only known *L. aurea* populations that occur in largely

natural conditions are those at Broughton Island, Lake Merero, Shoalhaven Heads and Kemblawarra (Pyke et al. 2001). In Victoria where *L. aurea* is found in several natural sites and is believed to be reasonably secure in terms of conservation (e.g., Gillespie 1996), most sites where the species still occurs are also largely or completely human-made (Pyke et al. 2001).

Individual

Physiology

Physiological studies of *L. aurea* have shown that this species is adapted more to a terrestrial life than to an aquatic one. Cree (1988) found that dehydrated frogs were able to absorb water relatively quickly through their ventral skin. Buttemer et al. (1996) found that the rates of evaporative water loss from frogs over a range of temperatures were indicative of a generally waterproof skin. This resistance to dehydration and ability to quickly rehydrate when able to contact a moist surface would be advantageous to this species in the context of basking, dispersal, foraging and other terrestrial activities.

Growth and development

Separate phases of growth and development occur during each of the five life history stages.

Egg hatching rates are affected by water temperature but may not be affected by pH. A significantly lower proportion of eggs hatched at 18 deg. C than at either 22 or 26 deg. C (Penman 1998). The proportion of eggs that hatched did not vary significantly across pH values of 4, 7 and 9 (Penman 1998).

Considerable growth and development occurs during the tadpole stage. It begins with hatching, which generally occurs about 2-5 days after spawning (McCann 1961; Ford 1983, 1986; van de Mortel 1996; Penman 1998; G. Daly, Nowra, pers. comm. 1999; White unpublished observations) but may occur within a few hours of spawning (McCann 1961). Upon hatching tadpoles are about 2.5 -3 mm in snout-vent length and about 5-6 mm in total length (Morgan 1995; Ford 1983, 1986; Penman 1998; White unpublished observations). Tadpoles in captivity increase exponentially in total length as they age, tripling in SVL from about 3 to about 9 mm within the first 35 days and tripling in length again in the next 35 days (Penman 1998). Morgan (1995) reported a growth rate of 0.2 mm per day that would apply to about the first half of a tadpole's life. The maximum observed size of

tadpoles in Australia has been about 100 mm in total length and about 30 mm SVL (Barker and Grigg 1977; Bell 1982a; Ford 1983, 1986; Barker et al. 1995; Daly 1995; Morgan 1995; Hobcroft 1997b; Hamer 1998; Penman 1998; White unpublished observations), while in New Zealand tadpoles may generally be larger, attaining a total length of up to 130-150 mm (Bell 1982a). Toward the end of the tadpole stage, hind limbs have appeared and become well developed, and front limbs have begun to develop. This stage ends when development of the front limbs is complete.

In natural situations the tadpole stage is usually completed during the period from October to April, as would be expected from spawning events during September to March. Tadpoles have, however, been observed in the wild during all months of the year, suggesting that they may sometimes overwinter as tadpoles (Morgan 1995; Pyke and White unpublished observations). In addition, some *L. aurea* tadpoles have overwintered as such in captivity (Hobcroft 1997b).

The duration of the tadpole stage, in both the wild and in captivity, is generally between 10 and 12 weeks but may range widely from about 5 weeks to about 12 months. Long tadpole duration may result in tadpoles having to survive over winter (Harrison 1922; Hoser 1989; Daly 1995; Morgan 1995; Hobcroft 1997b, Hamer 1998; Penman 1998; White unpublished observations). Some of this variation could result from a positive relationship between water temperature and growth, as the longer tadpole periods have generally been found to extend over the cooler months of the year (White unpublished observations).

Tadpole growth is affected by water temperature but may not be affected by pH. There was no significant variation in growth rate across pH values of 4, 7 and 9 (Penman 1998). In addition, for about the first 26 days, there was no significant variation in growth rate across temperatures of 18, 22 and 25 deg. C (Penman 1998). However, subsequent growth was significantly slower at 18 deg. C than at 22 deg. C (Penman 1998).

At the beginning of the metamorphling stage both front and hind limbs are present and well developed, and a tail is also present. During this stage the tail is resorbed, and the only other externally visible change is the closure of the spiracle. Metamorphlings typically have a SVL of about 22-28 mm (Daly 1995; Penman 1998; Pyke

and White unpublished observations) but can range from about 20 mm to about 37 mm (Hamer 1998; Pyke and White unpublished observations). SVL remains relatively constant during metamorphosis (Daly 1995; Hobcroft 1997b; Penman 1998; Pyke and White unpublished observations). This stage ends when resorption of the tail is complete.

The metamorphling stage lasts 3-8 days (White unpublished observations).

For *L. aurea*, the immature stage is also a time of considerable growth and development. The smallest frogs, which have presumably just completed metamorphosis, have SVL about 25-35 mm, which is similar to that observed for metamorphlings (Bell 1982a; Greer and Byrne 1995; Pyke and White unpublished observations). The initial growth rate of these frogs after metamorphosis is relatively rapid with frogs reaching 45 mm SVL within two months (Hamer 1998), 50-60 mm SVL within 6 months, and increasing in length more slowly after that (Pyke and White unpublished observations). In a captive situation, Robinson (1993b), for example, observed one individual grow from a 30 mm immature to a 64 mm adult in just under 10 months.

Males develop into reproductively mature adults earlier and at a smaller size than females. Observations of individual frogs of known age in both wild and captive situations indicate that male *L. aurea* are apparently able to breed as early as the spring following their hatching at an age of 6-9 months and a SVL of 50-60 mm, whereas females apparently do not breed until the next season when they are about 12 months older and at least 65 mm in SVL (wild: Greer 1995; Pyke and White unpublished observations; captive: Hobcroft 1997a). Adult males are generally observed to be about 55 to 70 mm SVL in the wild and occasionally reaching about 70-80 mm, while adult females are usually 70 to 85 mm and occasionally 85-95 mm SVL (Clyne 1969a; Moore 1961; Courtice 1972; Barker and Grigg 1977; Barker et al. 1995; White 1995a, Grenadier and Mahony 1999; Bauer and Sadlier 2000; Pyke and White unpublished observations).

It is possible that male and female immatures grow at the same rate. If metamorphlings are sexed on the basis of internal characters, no differences in body size are found between males and females (Greer and Byrne 1995). So they apparently start from the same point. The generally larger size of

adult females compared with adult males could arise from the extra year that female immatures grow before reaching reproductive maturity. However, whether there is any difference in growth rate is unclear as there are no available data on growth of immatures up to the size and age at which sex can be determined.

For males the immature stage ends when nuptial pads are developed at a SVL close to 50 mm. This threshold also marks the transition from immature to adult reproductive behaviour. Calling males have nuptial pads and SVL at least 50 mm (Pyke and White unpublished observations). Amplexing pairs involve males that have nuptial pads and are larger than about 50 mm SVL (Daly 1995; Pyke and White unpublished observations).

For females, however, the transition from immature to adult is far less clear. Amplexing pairs involve females larger than about 65 mm SVL (see above; Daly 1995; Pyke unpublished observations.), which suggests that females reach maturity at about this size. There is presently, however, no available information on the internal changes exhibited by females as they grow and develop.

Once adulthood has been reached there is apparently little or no further growth. In a captive situation, Robinson (1993b) observed an adult that increased in SVL from 74 mm to 80 mm over a 14-month period. Recaptured adult frogs in the wild have shown negligible growth (Pyke and White unpublished observations).

As *L. aurea* frogs increase in SVL they also tend to increase in body weight. Metamorphlings generally weigh about 2 g while the largest adults may weigh 50 g or more (Hamer 1998; Pyke and White unpublished observations). There is a strong positive correlation between SVL and body weight (Pyke and White unpublished observations).

However, individual frogs are likely to fluctuate significantly in body weight as a result of factors such as changes in amount of stored fat, recent food intake and egg formation. For example, when females spawn, they may lose up to 26% of their body weight (Hobcroft 1997a) and it is possible, therefore, that female body weight may provide a good indication of reproductive status (e.g., ready to spawn; recently spawned). Also male *L. aurea* have been found by Humphries (1979) to lose weight during the breeding season when they are doing relatively little feeding. He

found that male *L. aurea* showed an overall weight loss between August and December, the breeding period for his highland population, followed by recovery from January to September.

There has been only one report of developmental abnormality in *L. aurea*. Greer (1997) found that, from a sample of tadpoles collected from a highly polluted site in Sydney, half of the resulting metamorphosed frogs ($n=10$) showed a limb abnormality consisting of one or more supernumary bones. On the other hand visually detectable abnormalities are rare amongst *L. aurea* found at unpolluted sites on Broughton Island (Pyke unpublished observations).

Reproduction

Reproduction in *L. aurea* begins with pre-amplexus calling and courtship which may then be followed by amplexus and egg-laying. These two phases are considered separately below.

In *L. aurea*, calling is exhibited only by males (Ford 1983, 1986; Hero et al. 1991; Robinson 1993a; White 1995a), and is generally associated with warm, wet weather in spring and summer. Calling is more likely to be heard during the "warmer" months (i.e., about August or September to about February or March) than at other times (Fletcher 1889; Harrison 1922; Cogger 1960; Barker and Grigg 1977; Bell 1982a,b; Robinson 1993a; Barker et al. 1995; White 1995a; Bauer and Sadlier 2000). Calling has been recorded over a temperature range from 16-23 deg. C for the water and 14-25 deg. C (dry bulb) for the air (Ford 1983, 1986; Thomson et al. 1996; Hamer 1998). Calling is more likely to occur after moderate to heavy rainfall than during periods of little or no rain (White 1995a).

Males, sometimes in groups, may call at any time of day from in or near water. Calling is usually heard at night, but may also occur during the daytime, especially in response to either playback or imitation of the call (Harrison 1922; Moore 1961; Humphries 1979; Bell 1982a; White 1995a). Males usually call while floating partly-submerged in open water, but sometimes call while perched on low mats of emergent vegetation, the ground or vegetation near water (Harrison 1922; Littlejohn 1969; Courtice 1972; Barker and Grigg 1977; Dankers 1977; Humphries 1979; Bell 1982a; Hero et al. 1991; Robinson 1993a; Barker et al. 1995; Daly 1995; White 1995a; Australian Museum Business Services 1996a; Bauer and Sadlier 2000). Sometimes a number of males at the same pond

will call in what seems like a synchronised chorus (Courtice 1972; Barker and Grigg 1977; Dankers 1977; Humphries 1979; Brook 1980; Bell 1982a; Barker et al. 1995). Such choruses have been reported by Humphries (1979) to have leaders, the removal of which disrupts or inhibits the temporal pattern of calling.

Male *L. aurea* can be identified on the basis of their mating call, which is quite distinctive. It has been likened to droning or growling followed by several short grunts (Lucas and Le Souef 1909; Harrison 1922; Clyne 1969a; Barker and Grigg 1977; Bell 1982a,b; Gill 1986; Ford 1989; Hoser 1989; Osborne 1990; Hero et al. 1991; Barker et al. 1995; Thomson et al. 1996). Sonograms of courtship calls have been produced by Ford (1989) and Thomson et al. (1996).

Calling by male *L. aurea* is clearly a component of the process whereby males attract and mate with gravid females, as has been found for other Australian frogs (e.g., Littlejohn 1965, 1968). Amplexing frogs have only been observed at times when males have been calling (Pyke and White unpublished observations). Observations prior to and including amplexus indicate that a female first approaches a calling male and that when the female is about 10 cm from the male, the male moves around the female, climbs on her back and grips her in amplexus (White unpublished observations). Presumably the calling by the males plays a role in attracting females and promoting amplexus. However, the mechanisms that are involved here remain to be determined.

Amplexus usually occurs at night, during the time of year when males are calling, and is generally associated with wet weather. Amplexus is mostly observed during the period from October to February (Table 1) and after significant rainfall (Ford 1983, 1986). Amplexus has sometimes been

Table 1: Summary of observations made during period from 1969 to 2001 of *L. aurea* in amplexus

Month	Number of observations
August	1
September	1
October	7
November	5
December	4
January	4
February	7
March	2

observed during the day (Bell 1982a; Pyke and White unpublished observations).

Amplexing frogs may move some distance across the ground before eggs are laid in water. Amplexing frogs have generally been found on land in grassy areas, but have also been observed in water (Ford 1983, 1986; White unpublished observations). Amplexing frogs may move over 100 m before egg laying takes place (White unpublished observations).

Amplexus is axillary or pectoral with the male grasping the female with his forearms under the female's armpits (Fletcher 1889; McCann 1961; Humphries 1979; Bell 1982a; Tyler and Davies 1993, Hobcroft 1997b). A positive correlation has been found between the body sizes of males and females found in amplexus (Ford 1983, 1986).

Amplexus usually concludes with egg-laying by the female (White unpublished observations) and may last between about 10 minutes and 5 days. Amplexus that was artificially induced under laboratory conditions lasted about 50 hours on average (Ford 1983, 1986). Amplexus has been observed for *L. aurea* in captivity to last up to 5 days (Hobcroft 1997b). Amplexus has been observed for *L. aurea* in the wild to last between 10 min and 3.5 hours (White unpublished observations). Occasionally amplexus will end without egg-laying (White unpublished observations).

Egg-laying and fertilisation are generally complete within about five minutes (White unpublished observations obs.) and apparently involve coordinated actions by both male and female. Males and females remain in amplexus during egg laying, the male presumably depositing sperm into the egg mass or into the adjacent water as the eggs are laid (White unpublished observations). During spawning the male may 'paddle' his hind legs from time to time (McCann 1961), an activity that could facilitate fertilisation.

Litoria aurea lays relatively large egg masses, with egg numbers usually ranging from 2-6,000, but occasionally exceeding 11,000 per spawn mass (Humphries 1979; Daly 1995; van der Mortel and Buttemer 1996; Table 2). The overall average recorded clutch size is about 3773 (Table 2).

Eggs and tadpoles of *L. aurea* are generally found from about September to April (Fletcher 1889; Bell 1982a,b; Bauer and Vindum 1990; Daly 1995; Bauer and Sadlier 2000; Pyke and White unpublished observations). This corresponds to the calling and spawning period, which usually extends from early September to late February with the addition of about two months for the tadpole phase (Pyke, Penman and White unpublished observations). However, tadpoles are also found during the cooler months of the year, an indication that they sometimes overwinter as tadpoles (Pyke and White unpublished observations). Immatures generally appear in about December or January of each year (Pyke and White unpublished observations).

General behaviour and activity patterns

The behaviour of *L. aurea* has been little studied and documented records of behaviour by this species are anecdotal rather than the result of systematic observation. There is presently little available information with regard to the relative frequencies with which *L. aurea* are encountered in different activities or in different kinds of location.

As expected from the seasonal patterns of spawning and tadpole development, most observations of *L. aurea* tadpoles are made during the warmer months of the year from about September to April. During this time they are generally observed swimming about 0-30 cm below the water surface or stationary near the bottom of shallow ponds, sometimes between the bases of emergent aquatic plants (Anstis 1974; Daly 1995; Australian Museum Business

Table 2: Recorded numbers of eggs per clutch for *L. aurea* over period from 1969 to 2001

Information source	Sample size	Range	Average
Humphries 1979	1		5450
van de Mortel 1996; van de Mortel & Goldingay 1998	8	2,463-11,682	5706
White unpublished observations: Rosebery	18	1960-3890	3036
White unpublished observations: Eastlakes	4	2330-3410	2875
White unpublished observations: Other sites	3	2580-4270	3673
Sources combined	34	1960-11682	3773

Services 1996a; Pyke and White unpublished observations.). Tadpoles have occasionally been observed swimming together like a school of fish (Hobcroft 1997b; Pyke and White unpublished observations). They are also sometimes observed moving along various substrates with their mouths pressed against the substrate and leaving behind a trail of reduced algal growth (Pyke and White unpublished observations).

Most observations of immature and adult *L. aurea* are also made from about September to April. These frogs are generally seasonally “active” (i.e., they move from one place to another) during this time of the year, when they leave their “over-winter” shelter sites to forage and breed (Daly 1995; Pyke and White unpublished observations). During the cooler months of the year they mostly remain hidden and “inactive”, though they are believed to emerge to forage occasionally during periods of relatively warm, wet weather (Humphries 1979; Daly 1995; White unpublished observations). It has been suggested that they “hibernate”, “bruminate” or “aestivate” during this period (Fletcher 1889; McCann 1961; Humphries 1979; Daly 1995; Grenadier and Mahony 1999; Wellington 1995b) and some frogs that have been uncovered during this time have been apparently “torpid” (Humphries 1979) or “dormant” (Markwell 1984). However, the necessary physiological studies to verify these hypothesised processes have not yet been carried out. In addition, there are some sites where fewer frogs are encountered during the cooler months of the year, but some are always active regardless of the time of year (Pyke and White unpublished observations).

During their active time of the year, frogs of *L. aurea* have been encountered under shelter, courtship calling (mostly from water), hopping across the ground, sitting on the ground near water, sitting on vegetation near water, floating at water surface, and hopping out of vegetation onto the ground or into water (Harrison 1922; Clyne 1969a; Bell 1982b; Clancy 1996; Cogger 2000; Osborne and McElhinney 1996; Daly 1996; Australian Museum Business Services 1996a; Pyke and White unpublished observations). In addition, *L. aurea* is often found sitting in the sun (on emergent or floating vegetation, logs or the ground) on warm to hot and sunny days, apparently “basking” in the sun (Fletcher 1889; Barker and Grigg 1977; Dankers 1977; Humphries 1979; Bell 1982a,b; Hoser 1989;

Hero et al. 1991; Greer 1994; Daly 1995; Barker et al. 1995; Australian Museum Business Services 1996a; van de Mortel and Buttemer 1998). *L. aurea* has also been observed foraging on the ground and in grassy areas near their ponds, and occasionally amongst emergent vegetation and shrubs near their ponds (Courtice 1972; Courtice and Grigg 1975; Barker and Grigg 1977; Humphries 1979; Barker et al. 1995; White unpublished observations). They are sometimes found away from water bodies during prolonged rain periods (Barker and Grigg 1977; Bell 1982b; Barker et al. 1995; White unpubl).

Litoria aurea can reasonably be labelled as “semi-aquatic” and “non-arboreal” (e.g., Zweifel 1992). Though reasonably well able to climb, *L. aurea* are rarely arboreal and are mostly found in water, on emergent vegetation or on the ground (Moore 1957; Tyler 1992; Barker and Grigg 1977; Bell 1982a,b; Barker et al. 1995; White unpublished observations). They are mostly found less than 10 cm above ground-level and rarely found more than 1 m above the ground (Pyke and White 2000; unpublished observations).

Litoria aurea has been found to be “active” during both night and day (Fletcher 1889; Barker and Grigg 1977; Wellington 1995a; Markwell and Knight 1986; Robb 1986; Hoser 1989; Hero et al. 1991; Cogger 2000; Robinson 1993a; Barker et al. 1995; Pyke and White unpublished observations). Their movements during the day, however, are generally limited to emerging from a shelter site and moving to a basking site. They rarely feed during the day unless an insect flies or lands very close by (White unpublished observations). At night, by comparison, they are much more active, and it is during this time they do most of their foraging and dispersal (White unpublished observations).

When *L. aurea* individuals have been observed continuously for periods of time, they have been observed in a range of activities, but there have not so far been detailed and quantitative studies of how and where *L. aurea* individuals spend their time. When individuals have been followed as they moved from one area to another they have been observed crawling along vegetation or the ground, hopping or feeding (White unpublished observations.). When individuals within a pond have been watched they have been observed calling, courting, mating and feeding (Miehs and Pyke 2001; Pyke, White and

Miehs unpublished observations). It is also common to observe *L. aurea* sitting apparently motionless for many minutes at a time (Pyke and White unpublished observations).

Movements

The home range of individual *L. aurea* may range from less than 100 square metres, if all the necessary habitat requirements are close together (Murphy 1996; Pyke and White unpublished observations), to an area with maximum dimension at least 700 metres, if necessary habitat areas are relatively far apart or frogs need to travel large distances in search of food (Bell 1982a; Pyke and White unpublished observations). Adult *L. aurea* have, for example, been observed sheltering in residential gardens located 200-300 m from their breeding site (White 1993; Goldingay and Lewis 1999; Pyke and Bannerman unpublished observations) and individuals have been observed on the ground up to 400m or more from the nearest water (Table 3). Also White followed one foraging individual *L. aurea* for over 1.5 km one night (Cawood 1997; White unpublished observations).

Individual *L. aurea* are also capable of considerably longer movements from one place to another, possibly as a result of dispersal rather than a large home range. They have often, for example, been found at distances of 1-2 km from their breeding ponds and sometimes at distances of 10 km or more (Pyke and White unpublished observations). Also recaptures of marked frogs have shown that individual *L. aurea* have sometimes moved up to 2-3 km between successive capture locations (Pyke and White unpublished observations).

Foraging and diet

The diet of tadpoles in natural situations apparently varies with tadpole size and age, with carnivory becoming more prevalent with age. Small tadpoles (i.e., < 12 mm total length) are sometimes observed with their oral parts in

contact with submerged rocks or vegetation, suggesting that they are grazing the film of bacteria and/or algae growing on these substrates (Pyke and White unpublished observations.). Tadpoles which are larger but have not yet developed limb buds appear to be more herbivorous, rasping off algae and other vegetable matter from rocks, logs or aquatic plants (McCann 1961; Pyke and White unpublished observations.). Tadpoles with legs or limb buds are apparently both herbivorous and carnivorous in the wild, sometimes eating other tadpoles or dead aquatic insects (Cogger 1960; Morgan 1995; Hobcroft 1997a; White unpublished observations).

Observations in aquaria generally show these same dietary patterns, except that tadpoles of all sizes may be cannibalistic if overcrowded (White unpublished observations.). In captivity, furthermore, tadpoles have grown and developed on diets consisting of boiled lettuce and/or ground rat pellets or fish flakes (e.g., Webb 1994; Morgan 1995; Hobcroft 1997a,b; White unpublished observations).

Adult *L. aurea* have been observed in the wild feeding on a wide variety of food types, including both small vertebrates and invertebrates. These prey include other frogs (including their own species), lizards, crickets, cockroaches, dragonflies, grasshoppers, caterpillars, slugs, earthworms, molluscs, isopods, flies and tadpoles (Krefft 1863; Fletcher 1889; Lucas and Le Souef 1909; Copland 1957; McCann 1961; Ash 1968; Barker and Grigg 1977; Dankers 1977; Humphries 1979; Hoser 1989; Hero et al. 1991; Cogger 2000; Thurley and Bell 1994; Barker et al. 1995; Wellington 1995a; Cawood 1997; Bauer and Sadlier 2000; Miehs 2000; Table 4). They are mostly terrestrial in habits. Observations of foraging by immatures in the wild have not been reported.

The observed diet of captive frogs of *L. aurea* has been similar. In captivity, *L. aurea* has been found to feed on house crickets, fruit flies, domestic flies and maggots, mealworm beetles and larvae, silkworms, instar plague locusts, cockroaches, water snails, earthworms, and even mice and small tiger snakes (e.g., Copland 1957; Tyler 1976; Coupe 1993; Robinson 1993b; Hobcroft 1997b). Captive frogs do not, however, respond to food items that are dead or otherwise immobile (Hobcroft 1997b).

The sizes of a frog and its prey appear to be correlated (White unpublished observations).

Table 3: Summary of observations made during period from 1969 to 2001 of *L. aurea* at distances greater than 50m from water

Distance	Number of observations
50-100m	1
100-200m	2
200-300m	3
300-400m	2
>400m	3

Sub-adult *L. aurea* appear to hunt and feed mostly on relatively small insects, especially flying ones. Larger, adult frogs, on the other hand, appear to avoid small food items and to concentrate instead on larger terrestrial insects and small vertebrates.

It is unclear how selective *L. aurea* is in its diet. It has been suggested that *L. aurea* will feed on any moving prey that it can capture and fit in its mouth (Krefft 1863; White 1995a). Consistent with this is the large variation in observed diet from one time and place to another (Miehs 2000). However, as no animal is expected or observed to be completely unselective in terms of foraging (e.g., Pyke 1984), it seems likely that *L. aurea* is at least partly selective with regard to what it eats and other aspects of its foraging behaviour. It has not so far been possible to evaluate dietary selectivity by comparing prey items pursued and consumed with those encountered (Miehs 2000).

For individual *L. aurea*, time spent feeding and food consumption per day apparently depend on the age of the individual, time of year and whether or not breeding is occurring at the time. In captivity, Hobcroft (1997b) has observed higher food consumption per individual during the warmer months than when it is cooler (Hobcroft 1997b). In a natural highland population, Humphries (1979) found that *L. aurea* spent less time feeding during the times of breeding and "brumation" (i.e., hibernation), than at other times. In the same population he also found that newly metamorphosed immatures continue to forage later in the year than adults (Humphries 1979). Perhaps immatures must devote a relatively high amount of time to foraging in order to satisfy winter energy requirements, breeding frogs are prevented from simultaneously foraging and food requirements are relatively low during the cooler

months of the year?

Other behaviour

For *L. aurea*, recorded observations in relation to other kinds of behaviour are restricted to sheltering, calling, secretion, social and anti-social behaviour.

On both a daily and seasonal basis there are times when frogs of *L. aurea* are hidden from view and, if found, are usually under cover (e.g., Krefft 1863; Fletcher 1889; Humphries 1979; Bell 1982a; Greer 1994). During these times the animals are presumably taking "shelter" from factors such as the sun, the cold, predators or other frogs. They mostly exhibit this behaviour during daylight hours in the warmer months of the year and all day during the cooler months.

During both the breeding and non-breeding periods of the year *L. aurea* has been found sheltering under a variety of materials, including rock, vegetation, wood and various kinds of human debris, such as galvanised iron sheeting, other pieces of metal, cement pieces or blocks, wooden items etc (Bell 1982a; Greer 1994; Pyke and White unpublished observations). In addition, during the non-breeding period of the year (i.e., April to August) *L. aurea* has been found in less-accessible places, usually referred to as "over-winter" sites, such as in mud and under relatively substantial objects, including rocks, vegetation litter, garden sheds, timber piles, brick stacks and dumped garbage (Krefft 1863; Fletcher 1889; Humphries 1979; White unpublished observations.). Sometimes frogs have been found over-wintering in groups (Fletcher 1889; Humphries 1979).

Litoria aurea emits at least three distinct types of call, which may be labelled as courtship, contact

Table 4: Summary of observations of feeding by *L. aurea* over period from 1969 to 2001

Daytime or night time	Food type	Number observations
Day	Dragonfly	1
Night	Cockroach	5
Night	Cricket	6
Night	Frog (metamorphs/ immatures of same species)	6
Night	Frog (other species)	2 (1 <i>Crinia signifera</i> ; 1 <i>Limnodynastes peronii</i>)
Night	Praying Mantis	1
Night	Grasshopper	1
Night	Earthworm	1

and distress calls. These three calls, which have also been described as “drone”, “grunt” and “squeal/ shriek” (McCann 1961; Ford 1989), have distinctive sonograms (Ford 1989). The “drone” call corresponds to the courtship call as discussed above (Ford 1989). “Grunts” are commonly made when animals are touched and may be more common for males than for females (Ford 1989). If one male *L. aurea* attempts to amplex another male, the second male emits a “grunt” call and the first male abandons the activity (Ford 1983, 1986). “Squeals” or “shrieks” are made by adults of both sexes and by immatures, and seem to be a fear, distress or panic reaction (McCann 1961; Barker and Grigg 1977; Ford 1989; Hobcroft 1997b; Barker et al. 1995). *L. aurea* will sometimes emit these calls when they are picked up (McCann 1961; Barker and Grigg 1977; Hobcroft 1997b; Barker et al. 1995; Pyke and White unpublished observations). Immatures give squeal calls when grabbed by a predator (Miehs and Pyke 2001).

The following observations suggest that *L. aurea* produces bioactive skin secretions. If several frogs of this species are kept together in the same plastic bag for several minutes, they sometimes become surrounded by a frothy fluid (Pyke and White unpublished observations). If one rubs one’s eyes with fingers that have handled frogs of this species, they can sting and become watery (Pyke unpublished observations). Some frogs of other species have been killed when exposed to skin secretions of Bell frogs (Tyler 1976; Humphries 1979). While grasping *L. aurea*, they can become so slippery because of the slimy mucus they release that restraining them is difficult (Tyler 1976; Pyke and White unpublished observations). While handling *L. aurea* they, and one’s hands, are sometimes noticeably “acid-smelling” (Tyler 1992; Pyke and White unpublished observations). The function of these secretions is unknown.

Litoria aurea show signs of both social and anti-social behaviour. The “choruses” of calling males that are sometimes heard could result from either aggregation or mutual stimulation of calling males, or both. On the other hand, spacing and aggression between males may also occur. In a natural population, Humphries (1979) observed, for example, that calling male *L. aurea* exhibited spacing behaviour with conspecific callers not tolerated at distances of less than 1 m without vocal challenge. He also found that combat and

attempted male-male amplexus is commonly observed, that injury is common during combat and that most of their daytime effort seemed devoted to repelling other males. In a small artificial enclosure Ford (1986) found that an amplexing male may sometimes be displaced by another male, but he did not observe any conflicts between unamplexing male frogs.

Population

Abundance

Litoria aurea was formerly, from all accounts, extremely abundant in many areas where it occurred (e.g., Timms 1974, 1975; Tyler 1976; Bell 1982b; Wellington 1995a). In some areas it was probably the most commonly encountered of all frogs (Krefft 1863, 1866; Lucas and Le Souef 1909; Copland 1957; Wellington 1995b; Australian Museum Business Services 1996a), and it was sufficiently plentiful to be used for class dissections (Tyler 1976; Tyler and Davies 1993), to be collected as food for pet snakes (R. Goldingay, Southern Cross University, pers. comm. 1999), and to be collected as food by Aboriginal people (Krefft 1863, 1866; Copland 1957). There are, however, no available quantitative estimates of its original abundance. During the 1970s it was considered to be a common species by a number of authors (Barker and Grigg 1977; Barker et al. 1995). Some authors have mistakenly labelled it as a common species in relatively recent times (e.g., Tyler 1992; Coupe 1993).

Remaining populations appear, however, to be smaller, especially in New South Wales. For most sites in this state where the species is still found, the maximum number of adult *L. aurea* that have been detected per day is 20 or fewer (Pyke and White 1996). The largest known populations of *L. aurea*, where around 200 adult frogs have been detected on a single occasion, include those at Broughton Island (Pyke and White unpublished observations) and Kooragang Island (Hamer 1998; pers. comm. 1999) and capture/recapture studies suggest that these populations may each include about 1000 adults (Pyke and White unpublished observations; A. Hamer, University of Newcastle, pers. comm. 1999). In New South Wales there are only five other populations that could possibly be of comparable size. These are at Homebush Bay (Greer 1994, 1996b; Pyke 1995; White 1996; Australian Museum Business Services 1996a,b), Kurnell Peninsula (White 1997b; Gunninah Environmental Consultants 1996; Australian Museum Business Services

1996a,b,c; Greer 1996b), Lake Meroo (White unpublished observations), Culburra (Mahony 1996; Chafer 1996) and Crescent Head (Parsons 1999; R. Wellington, NSW National Parks and Wildlife Service, pers. comm., 1999).

Populations of *L. aurea* in Victoria and New Zealand may also be generally small. During our surveys of these two areas we have encountered only small isolated populations of the species and there are no verified records of large populations in either area (Pyke et al. 2001). However, since *L. aurea* does not appear to have undergone the same level of decline in Victoria as in New South Wales (Gillespie 1996; pers. comm. 1996), there may be populations of the species in Victoria that are as large as or larger than those in New South Wales. There are presently no available estimates for the sizes of any populations of *L. aurea* in Victoria.

The sizes of other introduced *L. aurea* populations in New Caledonia and Vanuatu are unknown, as there are no available estimates of population size of this species for either island.

There are presently no clear spatial or temporal patterns in population size for *L. aurea*. Relatively large populations of the species occur, for example, to the north of Sydney (Broughton Island, Kooragang Island), within the Sydney area (Homebush Bay, Kurnell), along the New South Wales coast to the south of Sydney (Coomonderry, Lake Meroo) and probably in northeast Victoria. There is presently no available information concerning how numbers of *L. aurea* in various age/sex categories change through time.

Such information should, however, become available in the future as long-term research projects involving capture/recapture are presently underway for many *L. aurea* populations. These populations include those at Broughton Island (Pyke and White unpublished observations), Kooragang (A. Hamer, University of Newcastle, pers. comm. 1999), North Avoca (Pyke and Bannerman unpublished observations), Yuraygir (R. Goldingay, Southern Cross University, pers. comm. 1999), Port Kembla (R. Goldingay pers. comm.), Long Reef (Pyke unpublished observations), Homebush Bay (G. Muir, Australian Museum Business Services, pers. comm. 1999), Kurnell (White unpublished observations), Arncliffe (White unpublished observations) and Marrickville (White unpublished observations).

There are presently no quantitative descriptions or models of population dynamics in *L. aurea*. The only available model is our qualitative breeding

presence/absence model (Pyke and White 1996).

Sex/age structure

The vast majority of encountered frogs of *L. aurea* have been adults rather than immatures (Pyke and White unpublished observations). It is not clear, however, whether this results from a relatively low abundance of immatures or differences in behaviour that renders immatures much less likely to be observed than adults.

The observed sex ratio in *L. aurea* depends on the age class and location. Amongst metamorphlings males and females are about equal in number (Greer and Byrne 1995). At breeding ponds adult males are generally far more abundant than adult females (Pyke and White unpublished observations obs.). Away from breeding ponds adult females are generally more abundant than adult males (Pyke and White unpublished observations).

Dynamics

The dynamics of *L. aurea* populations could be influenced by survival, reproduction, immigration and emigration, all of which directly influence the numbers of individuals, and by growth and development, which determine how quickly individuals change from one survival/reproductive category to another. This section deals with survival and reproduction. Growth and development were considered above. There is presently no available information concerning immigration and emigration.

Hatching rates for eggs of *L. aurea* are generally reasonably high, but they are affected by physical and chemical properties of the water in which they occur. Under natural conditions these rates usually range from 46% to 77% (46% - van de Mortel 1996; van de Mortel and Buttemer 1996; about 70% - Penman 1998; 77% - van de Mortel et al. 1998), but there is no available information regarding possible correlates with this variation. Laboratory experiments have shown that hatching rate is affected by both water temperature and acidity. It is apparently maximal when water temperature is 22 deg.C and declines with both higher and lower temperature (Penman 1998). It is reduced under acidic conditions (i.e., pH 4), while showing no significant difference between neutral and alkaline conditions (i.e., pH 7 and 9) (Penman 1998).

Survival rates of *L. aurea* tadpoles are assumed to be extremely low, given its relatively large clutch sizes and the relatively small number of adults

that are found.

Factors that are likely to affect the survival of *L. aurea* tadpoles include water temperature, water pH, loss of water, influx of saline water (as can occur when a site is adjacent to the ocean), influx of other toxic substances (as through pollution, for example), disease, food supply and predation. At present, however, there is information available only in relation to water pH, water temperature, predation and influx of saline water. In laboratory experiments pH varying between 4 and 9 had no significant effect on tadpole survival (Penman 1998). In the same laboratory experiments tadpole survival was significantly lower at a water temperature of 26 deg. C compared with 18 and 22 deg. C (Penman 1998). Field observations of ponds that are occasionally inundated by ocean waves indicate that *L. aurea* tadpoles are killed if salinity reaches about 8 parts per thousand (Pyke et al. 2001; Pyke and White unpublished observations).

Predation on *L. aurea* tadpoles has been observed or detected in the wild on very few occasions. Predators, in these cases, have come from a wide variety of animal groups and have included fish such as Plague Minnow *Gambusia holbrooki* (e.g., Morgan 1995; Morgan and Buttemer 1996; Pyke and White 1996, 1999b; Pyke and White 1996), birds such as White-faced Heron *Ardea novaehollandiae* (Bell 1982a), Swamp Harrier *Circus approximans* (Bell 1982a) and White Ibis *Threskiornis aethiopica* (Table 5), reptiles such as Long-necked Tortoise *Chelodina longicollis* (Table 5), Red-bellied Black Snake *Pseudechis porphyriacus* (Table 5) and Water Skink *Eulamprus quoyii* (Pyke and Miehs 2001), various kinds of aquatic invertebrate such as water beetles (Family: Dytiscidae) (Hamer 1998; Table 5), water scorpions (Family: Nepidae) (Table 5) and dragon-fly larvae (Order: Odonata) (Hamer 1998) and adults of the same species

(Miehs and Pyke 2001).

Other known or potential predators would, by virtue of their known feeding behaviour, include other introduced fish such as Redfin Perch *Perca fluviatilis* (e.g., Pyke and White 1999b), native fish such as Eel *Anguilla* spp, Empire Gudgeon *Hypseleotris compressa* (Pyke and White 1999b) and Fire-tailed Gudgeon *H. galii* (Pyke and White 1999b), and other birds such as Pacific Heron *Ardea pacifica* and Intermediate Egret *Ardea intermedia* (Blakers et al. 1984). There is presently, however, no quantitative information available on the extent of predation on *L. aurea* tadpoles by any kind of predator, nor on any impacts such predation may have on the tadpole population.

There is presently little available information concerning survival or longevity of *L. aurea* after metamorphosis. From observations of *L. aurea* in captivity, it would appear that frogs can be long-lived as a number of individuals are known to have been kept in captivity for periods in excess of 10 years, with the longest known captive life being 15 years (J. Barker, NSW National Parks and Wildlife Service, pers. comm. 1994). Most discoveries of dead *L. aurea*, with no signs of having been attacked, have been made during May and June (i.e., late-autumn/ early-winter) (Table 6), suggesting that mortality resulting from factors other than predation may be greatest

Table 6: Summary of records made during the period 1969 to 2001 of *L. aurea* found dead but without signs of having been attacked

Season	Number of records
Jan-Feb	1
March-April	2
May-June	30
July-August	12

Table 5: Summary of observations of predation on *L. aurea* tadpoles made during period from 1969 to 2001. All observations were made during the day.

Predator type	Number of observations
Bird	5 (2 White-faced Heron <i>Ardea novaehollandiae</i> ; 1 White Ibis <i>Threskiornis aethiopica</i> ; 1 Sacred Kingfisher <i>Halcyon sancta</i> ; 1 Laughing Kookaburra <i>Dacelo novaeguineae</i>)
Water Scorpion (Order: <i>Hemiptera</i> ; Family: <i>Nepidae</i>)	1
Water Beetle (Order: <i>Coleoptera</i> ; Family: <i>Dytiscidae</i>)	1
Long-necked Tortoise (<i>Chelodina longicollis</i>)	1
Red-bellied Black Snake (<i>Pseudechis porphyriacus</i>)	1

during this period. The capture/recapture studies mentioned above should yield further information concerning survival or longevity of *L. aurea* in the wild.

Factors that are likely to influence survival of *L. aurea* include pathogens, food supply, desiccation, predation and human activities such as collecting and driving motor vehicles. However, only for predation and pathogens is there any relevant information.

A wide variety of animals has been found or observed to prey upon frogs of *L. aurea*. Observed predators include snakes such as Red-bellied Black Snake *Pseudechis porphyriacus* (Krefft 1863; Table 7) and Tiger Snake *Notechis scutatus* (J. Cann, Yarra Bay, pers. comm. 1997), birds such as Laughing Kookaburra *Dacelo novaeguineae* (Table 7) and Sacred Kingfisher *Halcyon sancta* (Table 7), the introduced Black Rat *Rattus rattus* (Table 7), larger members of the same species (Hamer 1998; Pyke and White unpublished observations) and even large invertebrates such as Brown Mantis *Archimantis latistyla* (Tyler 1976). In addition, the remains of *L. aurea* frogs have been found in both the stomach and faeces of the Red Fox *Vulpes vulpes* (Daly 1995; White unpublished observations).

There is presently no other available information on the nature and extent of predation on *L. aurea* frogs though it would be expected that they would fall prey to a variety of other snakes and birds (Wellington 1995a; Tyler 1976).

Regulating factors

The distribution and abundance of *L. aurea* may be determined by a number of factors including the availability of food, shelter or other resources, the levels of predation or disease affecting tadpoles and frogs, direct human impacts (e.g., collisions with motor vehicles, collecting) and historical effects. So far, however, there have not been any studies which directly consider the potentially

regulating role of any of these factors. Instead, the best indications regarding their likely importance come from a consideration of the patterns of decline in *L. aurea*.

There is general agreement that the dramatic decline in the distribution and abundance of *L. aurea* in New South Wales has been the result primarily of habitat destruction, habitat modification and predation on eggs and tadpoles by the introduced Plague Minnow (e.g., Mahony 1993, 1997, 1999; Greer 1994; Daly 1995; Morgan 1995; Wellington 1995b; Goldingay 1996; Mahony 1996; Morgan and Buttemer 1996; Osborne et al. 1996; Pyke and White 1996; Gillespie 1997; Tyler 1997; Goldingay and Lewis 1999), and possibly disease (Mahony 2001).

Of these factors, *Gambusia* predation and habitat destruction have probably been the most important. For 93 sites in New South Wales where *L. aurea* vanished sometime before 1990, there is no remaining wetland habitat in five cases and an additional two are unclear in this regard (Pyke and White 1996; White unpublished observations). *Gambusia* is known to be present in 77 of the remaining 86 sites (Daly 1995; Pyke and White 1996; White unpublished observations). Though *L. aurea* may be found in or near ponds where *Gambusia* are present, it rarely breeds in such ponds (Wellington 1995a; Daly 1996; Pyke and White 1996). A number of experiments have, furthermore, demonstrated that *Gambusia* will feed heavily on the eggs and tadpoles of *L. aurea* and other frog species (Webb 1994; Morgan 1995; Morgan and Buttemer 1996; Webb and Joss 1997; Pyke and White 2000).

Other factors which may have been involved in the decline of *L. aurea*, and which have been suggested as being responsible for the observed worldwide declines in frogs, include global climate change, increases in UV-radiation through decreases in the ozone layer, extreme drought

Table 7: Summary of observations of predation on immature and adult *L. aurea* made during the period from 1969 to 2001.

Time of day	Predator Type	Number of observations
Day	Bird	1 (Sacred Kingfisher)
Night	Mammal	3 (Black Rat)
Night	Snake	2 (Red-bellied Black Snake)
Night	Bird	1 (Kookaburra)
Night	Snake or Eel	1 (In water)

and some kinds of pathogen or disease (van de Mortel and Buttemer 1996, 1998; Osborne 1990,1992; Osborne et al. 1996; Mahony 1996; van de Mortel 1996; van de Mortel 1996; van de Mortel and Buttemer 1996, 1998). However, *L. aurea* does not fit neatly into the general worldwide pattern of frog decline. Like many other frog species, the highland populations have declined more than the lower populations (Mahony 1996; J-M. Hero, Griffith University, pers. comm. 1999). However, the reduced highland populations of other frog species have generally been associated with stream habitats rather than ponds and swamps which are the principal habitat types for *L. aurea* (Mahony 1996; J-M. Hero, Griffith University, pers. comm. 1999).

Given the biology of *L. aurea*, increased UV-radiation could be a significant factor in the decline of this species. Both eggs and tadpoles generally occur near the surface in shallow water with high exposure to sun and the frogs often "bask" in the sun. Eggs of this species also show relatively low levels of photolyase activity and hence may be particularly sensitive to increases in UV-radiation (van de Mortel et al. 1998). However, the results of research on the possible effects of increased UV-radiation have so far been equivocal (Morgan 1995; van de Mortel 1996; van de Mortel and Buttemer 1996). Furthermore *L. aurea* tadpoles show little or no tendency to avoid exposure to UV-radiation when given the opportunity to avoid such exposure (van de Mortel and Buttemer 1998). This lack of response to UV-radiation could arise from the low extent to which UV-radiation is transmitted through *L. aurea* skin (van de Mortel et al. 1998).

Long-term weather trends seem unlikely to have been responsible for the decline in *L. aurea*. Drought, for example, is unlikely to have been a major factor in the decline of *L. aurea* as the species disappeared from sites that remained wet as well as those that dried out (Osborne 1990,1992; Morgan 1995). Global climate change also seems unlikely to have been a major factor in the decline of *L. aurea* as there has been no change in either the northern or southern limits to the range of the species (Pyke and White 1996) as would be expected with broad changes in rainfall or temperature.

It is not clear whether a pathogen has played a significant role in the decline of *L. aurea*. A chytrid fungus, which has been linked with

declines in other frog species, has so far been found in three populations of *L. aurea* (L. Berger, Animal Health Laboratory, pers. comm.1999). However, the fungus also occurs in soil and may always have had a quite broad distribution (Berger and Speare 1998; Berger et al. 1998). It is possible, furthermore, that it is the susceptibility of frogs to such a fungus that has increased, rather than the prevalence of the fungus itself. Some other factor could be responsible for changes in frog susceptibility (Alford and Richards 1997; Hero and Gillespie 1997).

Altered patterns of mortality due to predators or parasites could have played a role in the decline of *L. aurea*. Predation by the introduced Red Fox (e.g., Daly 1995, 1996; Tyler 1997) could have been involved as *L. aurea* has apparently disappeared from some areas where the fox is present but *Gambusia* is not, and the fox is known to eat adult *L. aurea* (Daly 1995; White unpublished observations). This possible factor has not, however, so far received much attention, and warrants further investigation (Tyler 1997). A number of parasites have been found on *L. aurea*, but it is not yet clear what effects they may have (Cleland and Johnston 1910; Metcalf 1923; Ash 1968; Delvinquier 1987,1988; Bauer and Sadlier 2000), and there is presently no available information concerning possible changes to the parasite loads experienced by *L. aurea*.

Human activities may be directly responsible for population losses in *L. aurea*. In areas where frog movement routes cross roads some frog mortality will result from collisions with cars and other vehicles, as has been noted in the Homebush Bay area (Pergolotti 1995), near Coomonderry Swamp (Daly 1996) and in the Pt Kembla area (van de Mortel et al. 1997, 1998; Goldingay and Lewis 1999). Human collecting could also affect *L. aurea* populations but there is no available information concerning its likely impacts on *L. aurea*.

Other factors may affect *L. aurea* populations as it has disappeared from some localities with no apparent cause (White 1995a; Tyler 1997).

Though *L. aurea* is not a forest species, Ehmann (1996) categorises it as being tolerant of selective logging, frequent fire in its habitat, and partial clearing.

Population genetics

Research on six Sydney populations of *L. aurea* and one from the Shoalhaven area (Colgan 1994,

1996, pers. comm.) indicates that genetic variation within populations of *L. aurea* is relatively low, possibly as a result of population decline and fragmentation. However these possible losses in within-population genetic variation are not presently high enough to seriously threaten the viability of these populations (Colgan 1994, 1996). There is also genetic differentiation amongst populations of *L. aurea*, at least at the regional scale, and possibly at the local scale (E. Burns, University of New South Wales, pers. comm. 2001). However, further research will be necessary before the patterns of genetic variation within and between populations are well understood, and before it is known whether the present sizes and isolation of *L. aurea* populations pose genetic problems in terms of population viability. Such a study is presently underway (E. Burns, University of New South Wales, pers. comm. 2000).

It is possible in the future that artificial translocation of *L. aurea* into existing populations may be seen as being of benefit to the species in terms of reducing any adverse impacts of inbreeding (or simply boosting numbers). However, Greer (1996a) argues against such translocations on the grounds that they could disrupt patterns of local genetic differentiation.

Community

In Australia *L. aurea* is rarely, if ever, the only frog species present at a site. The extremely common and widespread Striped Marsh Frog *Limnodynastes peronii* is almost invariably found at sites with *Litoria aurea* (Pyke and White 1996, unpublished observations) and the Common Brown Froglet *Crinia signifera* often co-occurs with *L. aurea* (Osborne and McElhinney 1996; Pyke and White 1996; unpublished observations). There are usually 5-6 other frog species co-occurring with *L. aurea*, but several more co-occurring species are sometimes found (e.g., Humphries 1979). The maximum number of other frogs species that has so far been recorded at sites with *L. aurea* is 14 over a 12 month period (Pyke and White 1996; unpublished observations).

In other parts of its present range, *L. aurea* is usually the only frog species present. In New Caledonia and Vanuatu the introduced *L. aurea* is the only frog species present (Bauer and Sadlier 2000). In New Zealand the introduced *L. aurea* is usually found on its own, occasionally with *Litoria raniformis*, another introduction from Australia, and rarely with *Litoria ewingi*, a third Australian species.

Throughout its range *L. aurea* has almost always been the only member of its species group present. It presently is the only member of its species group at all known locations in New South Wales and almost all known locations in Victoria and New Zealand (White and Pyke 1966; Pyke et al. 2001; Pyke and White unpublished observations). However it co-occurs with its close relative the Southern Bell Frog *Litoria raniformis* at a few sites in Victoria (W. Sherwin, University of New South Wales, pers. comm. 1995) and, as mentioned above, a few sites in New Zealand (Pyke et al. 2001). In the past it co-occurred with either *L. raniformis* or *L. castanea* at a few sites in New South Wales (Humphries 1979; White and Pyke 1999).

Ponds in which *L. aurea* is found are not necessarily constant in time but may undergo succession-like changes over time in both the nature and extent of aquatic vegetation and the relative abundances of *L. aurea* and other frog species present (Pyke and White 1999a). It has also been suggested that the suitability of a pond for *L. aurea* may decline as it is colonised and populated by other frog species (White 1995a; 1997b).

The patterns of co-occurrence of *L. aurea* and other frog species provide no indication of possible interactions amongst these species. There are no apparent frog species that, based on their known distribution and patterns of habitat-use, would be expected to co-occur with *L. aurea*, but do not. There is, furthermore, presently no information on whether the extent of co-occurrence of *L. aurea* with any other frog species is more or less than would be expected on this basis. A negative association between *L. aurea* and another similar frog species might suggest a competitive interaction between the two species.

Research techniques

The occurrence of *L. aurea* at or near a site may be determined through direct or indirect observation, or through the discovery of remains of the species. The species may be detected at a site either through direct observation of its tadpoles or frogs, or through hearing males calling (e.g., Daly 1995; Ehmann 1996; Australian Museum Business Services 1996a,b; Osborne and McElhinney 1996; Goldingay and Lewis 1999; van de Mortel and Goldingay 1998). Males can often be stimulated to call through either someone imitating their call or through playback of a sound-recording of the call of the species (Hobcroft

1997b; van de Mortel and Goldingay 1998; Pyke and White unpublished observations). The recent presence of *L. aurea* at or near a site can potentially be discovered through finding remains of the species in scats or stomachs of predators such as foxes and cats (Daly 1995; Osborne et al. 1996). The past occurrence of *L. aurea* at a site may be determined through either the discovery of the remains of bones of the species (M. Tyler, University of Adelaide, pers. comm. 2000) or through examination of photographic records of frogs from particular sites (e.g., Pyke and White 1999).

No special techniques have been developed for observing or monitoring *L. aurea* either in the wild or in captivity, but techniques adopted for other frog species are generally applicable to *L. aurea*. *L. aurea* may be observed during the daytime under natural light and at night with some kind of artificial illumination. Immatures or adults may be followed at night by a person who walks several metres behind them and occasionally illuminates them with a light covered with red cellophane (White unpublished observations). Using this method it has been possible to follow frogs for up to 6 hours during one night. It may also be possible to observe *L. aurea* at night with the aid of an image-intensifying device (Cawood 1997). After attaching a small radio-transmitter to the back of a *L. aurea* with a harness arrangement, radio-tracking techniques can be used to follow the movements of such a frog over a period of up to several weeks (M. Mahony, University of Newcastle, pers. comm. 1999). However, this technique suffers from a number of difficulties such as harness loss and entanglement of the aerial in undergrowth (M. Mahony, University of Newcastle, pers. comm. 1999). Information about the movements of *L. aurea* may also be obtained by comparing the successive locations of captures of the same (marked) individual (Pyke and White unpublished observations).

Capture method varies with the life-history stage involved. Tadpoles or metamorphlings of *L. aurea* may be captured with a small-mesh hand-net, in "bait traps" (i.e., small clear, submersible containers with inverted funnel-shaped entrances), or occasionally by scooping with a plastic bag (Pyke and White unpublished observations). Metamorphling, immature or adult *L. aurea* are usually captured at night. A person quietly approaches or "stalks" a frog, while shining a light directly onto the frog and

avoiding unnecessary disturbance of the frog's surroundings, and swiftly "grabs" the frog when it is close enough (Pyke and White unpublished observations). Sometimes the stalking process may involve lifting up objects that may have frogs sheltering beneath them. Provision of artificial easy-to-lift shelter sites such as roof tiles or pieces of wood, may make it possible to capture frogs with little or no disturbance of other habitats (Greer 1994; Pyke 1995). If square-shaped artificial shelter boards are provided for the frogs, a small cage placed around the board before it is lifted may prevent some of the frogs that are sheltering beneath it from avoiding capture (Pyke unpublished observations). Pit-trapping has occasionally resulted in capture of *L. aurea*, but has generally been found to be ineffective (Dankers 1977; Australian Museum Business Services 1996a; White unpublished observations).

Handling methods also depend of the life-history stage involved. After capture *L. aurea* tadpoles may be kept in almost any water-holding container while waiting to be "processed", so long as they are also kept cool and out of direct sun (Pyke and White unpublished observations). After capture metamorphling, immature and adult *L. aurea* may be kept in a moist or partly wet plastic bag or similar container, so long as these are also kept cool and out of the direct sun (Pyke and White unpublished observations). *Litoria aurea* tadpoles are not usually touched but placed in a shallow container such as a Petri dish for detailed observation or measurement (Pyke and White unpublished observations). Metamorphling, immature or adult *L. aurea*, on the other hand, may be held in the hand during measurement, other observations and microchip implanting (Pyke and White unpublished observations). Most people use an uncovered hand, but gloves may be considered necessary where there may be a risk of human-enhanced spread of some pathogen (Speare et al. 1999; G. Marantelli, Amphibian Research Centre, pers. comm. 1999).

Different methods can be used to mark or identify individual frogs, depending on animal size and the total number of individuals involved. Regardless of size, both immature and adult *L. aurea* may be individually "marked" through the removal of fingers or toes from captured frogs (i.e., "toeclipping"- Humphries 1979; Hero 1989; Heyer et al. 1994). The combinations of digits

removed can allow for many individual frogs to be individually identified (e.g., Hero 1989; Heyer et al. 1994). *L. aurea* that are greater than about 40 mm in snout-vent length can be “marked” through the insertion under the abdominal skin of a passive integrated transponder (i.e., PIT tag or “microchip”) (Christy 1996). In addition, if the total number of individuals is not too great, it may be possible to recognise individuals on the basis of their dorsal markings (Clyne 1969a; Bell 1982a; Ford 1983, 1986; Greer 1994; Wellington 1995a; Murphy 1996). However, this technique cannot be used over long time periods as body markings change with age (White and Pyke unpublished observations). No technique has been developed or adopted for individually marking tadpoles.

Toe-clipping or the insertion of microchips does not appear to alter frog survival. Humphries (1979) found non-significant relationships for adult males, adult females and immatures, between the proportion recaptured and the number of toes removed, suggesting that toeclipping had no adverse effects. In addition, Christy (1996) has indicated that microchipped frogs in captivity did not show any significant change in body weight and hence may have been unaffected in terms of appetite and mobility. She also reported that she had microchipped 194 free-living *L. aurea* without observing any apparent adverse effects. We have microchipped over 1000 *L. aurea* with high recapture rates and without any obvious resulting mortality (Pyke and White unpublished observations).

It is not clear how long either of these two kinds of “mark” will last. Some observations suggest that *L. aurea* digits will regenerate (White unpublished observations; T. Penman, University of New South Wales, pers. comm. 1998) and some microchipped frogs have been observed in captivity to lose their chips over periods of several months (Hobcroft 1997b; G. Muir, Australian Museum Business Services, pers. comm. 2000). On the other hand frogs with digits removed have been caught up to two years later still showing clear signs of the initial removal and frogs with microchips inserted in the wild have been recaptured at least two years later still carrying the microchips (Pyke and White unpublished observations).

The method for releasing captive animals depends on the life stage involved but, in any case, is relatively simple. Release of *L. aurea* tadpoles or metamorphlings involves either pouring them

and their surrounding water into some other water body or placing their container in the water and either opening the door or removing the lid (Pyke and White unpublished observations). Release of metamorphling, immature or adult *L. aurea* generally involves either releasing one’s grip around them and allowing them to move away or opening their bag or other container and allowing them to hop out (Pyke and White unpublished observations).

In New South Wales, the National Parks and Wildlife Service has issued protocols for the safe handling of frogs (NSW National Parks and Wildlife Service 2000). These protocols also apply to *L. aurea*.

Conservation and management

The present designated conservation status of *L. aurea* varies between state and country. In New South Wales *L. aurea* species is legally listed as “endangered” on Schedule 1 of the New South Wales Threatened Species Conservation Act 1995 (i.e., it may already be extinct or it is considered likely to become extinct in nature unless the circumstances and factors threatening its survival or evolutionary development cease to operate). The Frog and Tadpole Study Group of New South Wales lists *L. aurea* as being “endangered” in New South Wales on the basis of International Union for the Conservation of Nature Criteria (International Union for the Conservation of Nature 1994; Ehmann 1996). At a National level *L. aurea* is considered “endangered” in the National Frog Action Plan (Tyler 1997) (i.e., considered to be a “species in danger of extinction and whose survival is unlikely if causal factors continue to operate, including species that may already be extinct”), but it has only recently been added to the National list of “vulnerable” species under the Commonwealth Endangered Species Protection Act 1992 and under its replacement the Environmental Protection and Biodiversity Conservation Act 1999 (Edgar and Stephens 1993; Commonwealth of Australia 1999) (i.e., within the next 25 years, the species is considered likely to become “endangered” unless the circumstances threatening it cease to operate), and it is not included on the list of endangered species under either Act. *Litoria aurea* is not listed as either “threatened” or “endangered” under the Victorian Flora and Fauna Guarantee Act 1988 (Mansergh et al. 1993). Amongst other animal species of the world *L. aurea* is listed as “LR/nt” on the 1998

IUCN Red List of Threatened Animals (World Conservation Monitoring Centre 1999) (i.e., considered to be of relatively low risk of extinction but close to qualifying as "vulnerable"). In New Zealand, *L. aurea* is an unprotected feral species.

Populations of *L. aurea* are not well protected within conservation reserves. Of the roughly 40 known populations of *L. aurea* in New South Wales that have been recorded since 1990 (Pyke and White 1996; unpublished observations), only eight include breeding sites that are within a conservation reserve. All other populations breed only on private land (Pyke and White 1996, unpublished observations; Australian Museum Business Services 1996a). Populations that breed within conservation reserves but do not apparently occur entirely within these reserves include those at Crescent Head in Crescent Head National Park (R. Wellington, NSW National Parks and Wildlife Service, pers. comm. 1999), Coomondery Swamp in Seven Mile Beach National Park (Murphy 1994; Daly 1996; Pyke and White 1996; White unpublished observations) and Cox's Creek in Cox's Creek Reserve (White 1993; Pyke and White 1996). *L. aurea* has also been found within Botany Bay National Park but apparently does not breed within the park (Australian Museum Business Services 1996b; White unpublished observations). It breeds instead in a number of nearby parts of the Kurnell peninsula that are privately owned (Australian Museum Business Services 1996a,b). The only known populations of *L. aurea* which apparently occur totally within a Conservation Reserve are those in Yuraygir National Park (Clancy 1996; Pyke and White 1996), Myall Lakes National Park (Bombah Point and Smith's Lake: Markwell and Knight 1996; Pyke and White 1996; M. Mahony, University of Newcastle, pers. comm. 1996; White unpublished observations; Broughton Island: Pyke and White unpublished observations) and Jervis Bay National Park (Marshall's Beach/Ryan's Swamp: Osborne et al. 1996; Pyke and White 1996; Bowen Island: Osborne and McElhinney 1996; Osborne et al. 1996; Pyke and White 1996; Daly 2000).

The official endangered status of *L. aurea* in New South Wales seems well justified. It was once one of the most commonly encountered frogs in this State, being widespread in coastal lagoons and swamps between about Byron Bay and the Victoria border and in wetlands on the western slopes and tablelands from about Bathurst to the Southern Highlands (Pyke and White 1996). Since 1990, however, the species has been found

at only about 40 sites in the State and its populations at these sites are generally quite small (Pyke and White 1996). This dramatic decline in the species is apparently continuing with at least 4 of the populations in the Greater Sydney Region having apparently been lost during just the last 5 years (i.e., Rosebery, Mt. Druitt, Williams Creek, Voyager Point; see Pyke and White 1996). Almost all the remaining populations of the species in New South Wales are outside of conservation reserves and are therefore under continuing threat from various human activities. This situation in New South Wales is reflected in the determination made by the Scientific Committee working under the New South Wales Endangered Fauna (Interim Protection) Act 1991 when it concluded that the species should be listed as threatened, then the top category, which has now been altered to the standard "endangered" under the Threatened Species conservation Act 1995. It made this decision on the basis that *L. aurea* in New South Wales has a population which has been severely reduced over its entire range and that the species is subjected to severe threatening processes (Lunney et al. 1996, 2000).

For the following reasons we consider that *L. aurea* is "vulnerable" in Victoria and likely to become "endangered" there in the near future. In Victoria *L. aurea* has so far avoided the precipitous declines of New South Wales. There are, for example, few populations of the species in this state that are known to have disappeared (Gillespie 1996). There is, nevertheless, considerable cause for general concern about the species in Victoria. A few sites away from the coast, which once supported the species, no longer have suitable breeding habitat and the species has not recently been found there. Populations near the coast apparently remain extant but have apparently decreased in size in at least one case (Pyke and White unpublished observations). East Gippsland, the area in Victoria where *L. aurea* is mostly found, appears to be largely devoid of the introduced Plague Minnow, which eats eggs and tadpoles of this and other frogs, is considered to have been one of the factors responsible for the New South Wales decline and has recently been listed as a Threatening Process under the New South Wales Threatened Species Conservation Act 1995. This fish is, however, abundant just over the NSW border and also further to the west in Victoria and it seems likely that its invasion of East Gippsland is only a matter of time (Tyler 1997). When the

Plague Minnow does arrive, its effect on *L. aurea* populations could be devastating.

Taking New South Wales and Victoria together, *L. aurea*, while probably not being “endangered” at present, is clearly “vulnerable” and seems very likely to soon become “endangered” (see also Goldingay 1996). Overall it has been lost from over 80% of its distribution prior to European settlement, with this decline being apparently due in large part to predation by the Plague Minnow (see above), which now threatens to invade areas in Victoria where the frog species occurs. The National listing of *L. aurea* as vulnerable under the Commonwealth Endangered Species Protection Act 1992 therefore was appropriate, as is its present listing under the Commonwealth Environmental Protection and Biodiversity Conservation Act 1999, while its listing as endangered in the National Frog Action Plan (Tyler 1997) was probably a wise precaution.

Management of *L. aurea* with the goal of species recovery must address current threats, which include habitat loss, further spread of *Gambusia*, further spread of pathogens, potential inbreeding depression, and benign neglect (Goldingay 1996; Pyke and White 1996; Ehmann 1996; Goldingay and Lewis 1999). Habitat loss is a serious threat to *L. aurea* because the owners of land upon which *L. aurea* is found may seek to develop the land in ways that are detrimental to the frog. The site of the *L. aurea* population at Rosebery was destroyed, for example, as part of a building development (NSW National Parks and Wildlife Service 1994; Wright 1996).

The current risk from pathogens is unclear. However, as the decline of some frog species has been linked to pathogens and some *L. aurea* populations have been found to have individuals infected with a pathogen, this risk must be considered and precautionary steps taken (NSW National Parks and Wildlife Service 2000).

Because the remaining *L. aurea* populations are now isolated from each other and generally small, increased inbreeding in these populations may also occur and this may, through inbreeding depression, increase the risk of population extinction (Frankham 1995). It may therefore be considered necessary to artificially increase the level of gene flow between populations through the translocation of individuals from one site to another.

An approach of “benign neglect” may also be

inimical to the long-term viability of some populations of *L. aurea*. In some situations the frog may survive because of the inadvertent effects of ongoing site management and may cease to survive if this form of management ceases or changes. A population may, for example, remain and successfully breed in a pond at the North Durras Caravan Park because the water in the pond is constantly replaced as a result of its use within the park and/or because the pond regularly receives an application of bentonite, which may stimulate appropriate growth of algae and bacteria. If these practices ceased and the pond was simply “left alone”, the pond might steadily become less suitable for the frog and the population could decline.

With regard to potential recovery of *L. aurea* there is also a number of opportunities, which include enhanced legislative protection, conservation agreements, habitat creation, habitat enhancement, habitat modification to reduce the impacts of *Gambusia*, reduction in *Gambusia* numbers and translocation of individuals. Enhanced legislative protection could benefit *L. aurea* because any loss of habitat for *L. aurea* is generally the result of human decisions, with landholders deciding upon the ways they would like to develop their properties and Government agencies deciding whether or not to approve any proposed development and what conditions to impose in association with any approval. As these decision-making processes are influenced by legislation, it should be possible to alter the legislative constraints in ways that increase protection for remaining populations of *L. aurea*. It would be possible, for example, for some or all of the remaining areas of habitat occupied by *L. aurea* in New South Wales to be declared “critical habitat” under the New South Wales Threatened Species Conservation Act 1995, thus increasing the onus on all parties to protect these areas. The recent declaration of *Gambusia* as a threatening process under the same legislation could similarly benefit *L. aurea*.

Conservation agreements could also benefit *L. aurea*. In a number of jurisdictions conservation agreements may be established between landholders and Government agencies whereby the landholder agrees to conserve the natural environment in some way while the Government agency may provide some form of assistance or encouragement for the landholder. Since so many *L. aurea* populations occur on private land, there must be considerable potential for the development

of such conservation agreements that feature *L. aurea*.

While probably not being feasible for most frog species, habitat creation could be of benefit *L. aurea*. Because most sites where *L. aurea* occurs are heavily disturbed by human activities and many are largely or completely human-made, it should be possible, given the correct guidelines, to replicate the habitat conditions of these sites at new sites (Pyke and White 1996). However, since not all kinds of human disturbance are apparently suitable for *L. aurea*, it will be necessary to determine these guidelines as precisely as possible before successful habitat creation for *L. aurea* can be expected. New habitat for *L. aurea* has so far been developed or proposed for six populations within the Sydney area (Enfield - Greer 1995; Kurnell Peninsula - Gunninah Environmental Consultants 1996; McKenzie Land Planning Services 1996; Australian Museum Business Services 1996b; Jensen 1997; Homebush Bay Olympic Site, Homebush Bay - Homebush Bay Corporation 1994; Australian Museum Business Services 1996b,c; Sir Joseph Banks Park, Botany - Fanning 1996; Port Botany; Long Reef Golf Course, Collaroy - Pyke unpublished observations; Marrickville Community Centre, Marrickville - Voigt 1996.) and two populations outside of the Sydney area (Ravensworth - Resource Planning Pty Ltd 1994; Interagency Advisory Group 1994; Port Kembla - van de Mortel et al. 1997, 1998; Goldingay and Lewis 1999). If not already present in the vicinity of any newly-created habitat individual *L. aurea* would have to be translocated to the site (Goldingay 1996). It is not yet clear how successful these programs with their associated introductions or colonisations of *L. aurea* have been. Habitat creation would undoubtedly be much more difficult for species that require undisturbed habitat.

Habitat enhancement could likewise benefit *L. aurea*. Because of the potential to create new habitat for *L. aurea* and the identification of certain reasonably specific habitat requirements such as shelter sites, areas for foraging and places for basking (e.g., Pyke and White 1996), it should similarly be possible to enhance the habitat for *L. aurea* by adding certain habitat resources. Emergent aquatic plants could, for example, be introduced into a pond that lacked them.

It may also be possible to either reduce the numbers of *Gambusia* that are present or reduce their impact through habitat modification. Some sites exist where *L. aurea* apparently coexists and

even breeds with *Gambusia* present (van de Mortel 1996; Pyke and White 1996; van de Mortel and Goldingay 1997; Goldingay and Lewis 1999; Hamer 1998; Gillespie and Hero 1999). If the conditions that allow this coexistence can be determined then it may be possible to modify other sites where *Gambusia* is present so that *L. aurea* may be re-introduced (Goldingay 1996; van de Mortel and Goldingay 1997). It may be possible to reduce the numbers of *Gambusia* through such means as poisoning, the introduction of a *Gambusia*-specific pathogen or the use of native predatory fish (White 2001). Poisoning is unlikely to be effective, however, unless the volume of water to be treated is not too great and there are not places where the fish can retreat from the effects of the poison. Potential poisons include liquid chlorine, lime and rotenone (e.g., Goldingay 1996; Hamer 1998; Gillespie and Hero 1999; Grenadier and Mahony 1999). Reduction of water level followed by application of one or other of these poisons has been used at several sites (W. Meikle, Taronga Zoo, pers. comm. 2000; Pyke unpublished observations; J. Weigel, Australian Reptile Park, pers. comm. 1998). Results have so far been mixed (W. Meikle, Taronga Zoo, pers. comm. 2000; Pyke and White unpublished observations; J. Weigel, Australian Reptile Park, pers. comm. 1998). Pilot studies using *Glossamia* aprion have indicated that there is some potential to use this fish to eradicate *Gambusia* in confined ponds (White 2001).

In some circumstances translocation of individuals may also prove beneficial to *L. aurea*. The artificial movement of animals from one population to another might, for example, be considered to alleviate problems arising from inbreeding in the second population. The release of animals at a particular site could be part of attempts to either enhance numbers in an existing population or establish a new population in the wild. Translocation can also, however, have potentially detrimental consequences through alteration of the genetic composition of populations (e.g., Greer 1996a).

In programs that involve translocating *L. aurea* from one site to another tadpoles are generally used, rather than frogs, because it is considered likely that any imprinting on a pond will occur during or at the end of the tadpole phase (Greer 1994; Cooke and Oldham 1995). There has, however, been no evaluation of alternative procedures in translocating this species.

Captive husbandry

For *L. aurea*, and many other species of organisms, captive husbandry can potentially benefit both research and conservation interests. Research can be facilitated through the provision of animals for study or situations where they can be relatively easily observed (e.g., Penman 1998). Conservation efforts can sometimes be aided through the provision of animals for release into the wild.

Several captive breeding programs for *L. aurea* have now been established. One was commenced at Taronga Zoo, Sydney in 1994 with animals from a population at Rosebery. In 1997 the Australian Reptile Park in Somersby, New South Wales acquired *L. aurea* from several sites on the New South Wales Central Coast with a view to establishing a captive breeding program (R. Porter and J. Weigel, Australian Reptile Park, pers. comm. 1997). Captive breeding programs have also been developed at the University of Newcastle (M. Mahony, University of Newcastle, pers. comm. 2000) and at a private home near Merimbula on the south coast of New South Wales (Anonymous 2000).

Litoria aurea has been found to be a reasonably easy species to maintain and breed in captivity with a variety of situations apparently proving suitable. At Taronga Zoo, for example, breeding has occurred in indoor aquaria, aquaria placed outside and in a former aviary provided with several small in-ground pools (Hobcroft 1997a, pers. comm.). Breeding by *L. aurea* has occurred here in each of the last 5 years with passage now through to at least the second generation after the original adult stock (Hobcroft 1997a, pers. comm.). Successful captive breeding has also been achieved at the University of Newcastle (M. Mahony, University of Newcastle, pers. comm. 2000) and near Merimbula (Anonymous 2000). On the other hand, captive breeding has not so far occurred at the Australian Reptile Park (R. Porter, Australian Reptile Park, pers. comm. 2001), thus indicating perhaps that requirements for captive breeding are not fully understood.

Discussion

Compared with other Australian frog species, *L. aurea* has been relatively well-studied. There are, for example, at least 40 publications in scientific journals or books with the name of this species (either common or scientific) in the title (see Reference section below). There are also many

theses, reports and other documents that deal with this species (see Reference section below).

There are, however, many areas where further research on *L. aurea* is warranted. There has not, for example, been any evaluation of alternative methods for estimating population sizes, and no accurate estimate of the size of any population. We do not know the relative importance of different factors in determining population size, nor quantitatively how these factors operate, and this severely limits our abilities to manage populations. We do not, in particular, properly understand the patterns of habitat use by *L. aurea* and how these patterns affect survival and reproduction of the species, the circumstances and processes that permit *L. aurea* to occur and breed with *Gambusia* present in the same water body, or the incidence and influence of pathogens such as Chytrid fungus in populations of *L. aurea*. As always, there is much to be done.

Enough is known about the biology of *L. aurea* to enable decisions to be made and actions taken with a view to providing it with improved protection and management. Likely breeding, foraging and sheltering areas can be identified and protected (e.g., Greer 1994; Pyke 1995). Movement corridors can be planned (e.g., Pyke 1995). Breeding habitat can be developed or enhanced (e.g., Pyke 1995; Pyke and White 1996). Further research should refine these decisions and actions.

The biology of *L. aurea* seems enigmatic in that it has many attributes of “weedy” or “colonising” species and yet has declined in distribution and abundance to the point of being “vulnerable” at best and “endangered” at worst. In many respects it occupies a wide range of habitats and it is generally found in sites that are either highly disturbed or, in many cases, completely human-made. It is a relatively large, long-lived and highly-fecund species, capable of dispersing long distances between sites and surviving long periods between times of suitable breeding conditions. In most, if not all, these respects it is similar to *Lim. peronii*, a species with which it usually co-occurs and which is extremely common and widespread in south-eastern Australia. It is not presently clear why *L. aurea* is rare and *Lim. peronii* is common.

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